Photovoltaic Power Systems
and
The 2005/2008 *National Electrical Codes*
A Presentation for
Electrical Inspectors, Electrical Contractors, and PV Professionals

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Southwest Technology Development Institute

College of Engineering
Institute for Energy & the Environment

Overview

- Introduction & Background
- Introduction to PV Systems
- PV Systems & *NEC* Requirements
- The *2008 NEC* and other material

Background and Introduction
Southwest Technology Development Institute

- Provide National & International Training
- Research & Implement *NEC*
- Review & Assist with UL & IEEE Standards
- Review System Designs
- Evaluate Proposals
- Design PV Balance of Systems Equipment
- Develop Prototype PV & Ground-Fault Hardware
- Test & Evaluate PV Systems
- Develop Data Acquisition Systems
- Monitor Resources & Assess System Performance

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Objective and Method

Objective: **Widespread Use of Safe, Durable, & Cost Effective Photovoltaic Power Systems**

Knowledgeable People Who Can Effectively Design, Install, & Inspect PV Systems

Method: **Maximum Interchange of Data Between the Research Community, the PV Community, and the Electrical Inspectors**

Introduction to PV Systems

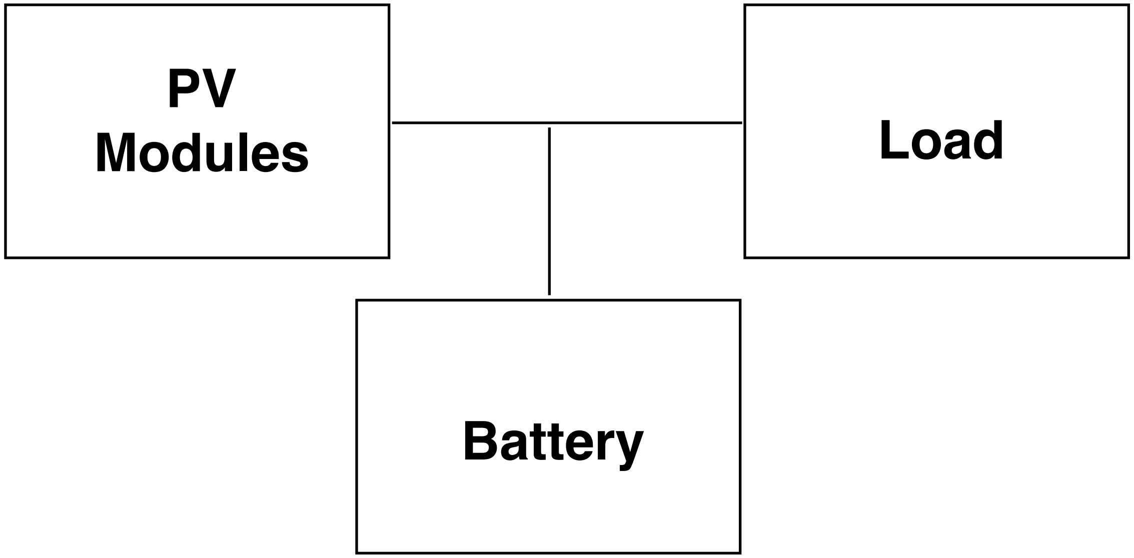
- **PV Systems are like other electrical power systems**
- **6 V to 1200+ V DC, 120 V - 480-12KV V AC**
- **1 A to 2000+ A DC**
- **Low voltage/high current & high voltage/low current**
- **6 W to 1megW to 14 megawatts and increasing**
- ***All systems have potential to harm people & damage property***

Introduction to PV Systems

Direct Connection PV System

- **Simple, reliable - No sun, No energy**
- **DC output**

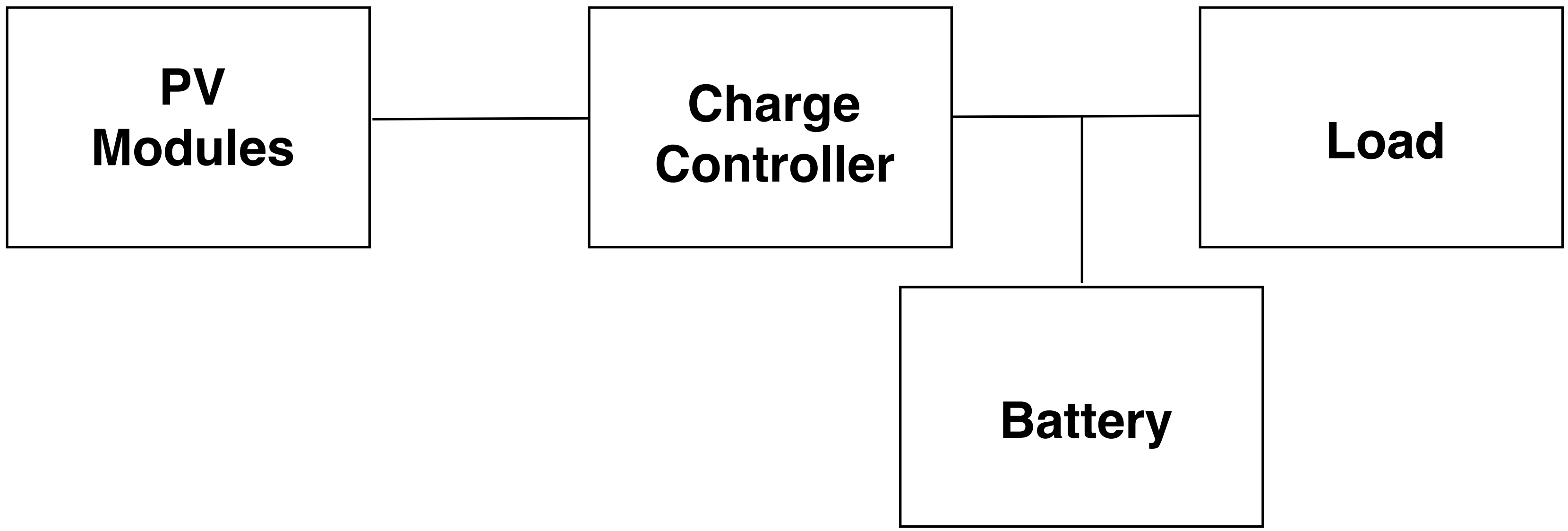
Introduction to PV Systems



Self Regulating Stand-Alone PV System

- For constant, small loads
- Does not manage the battery state of charge
- Night/cloudy day operation possible
- DC output

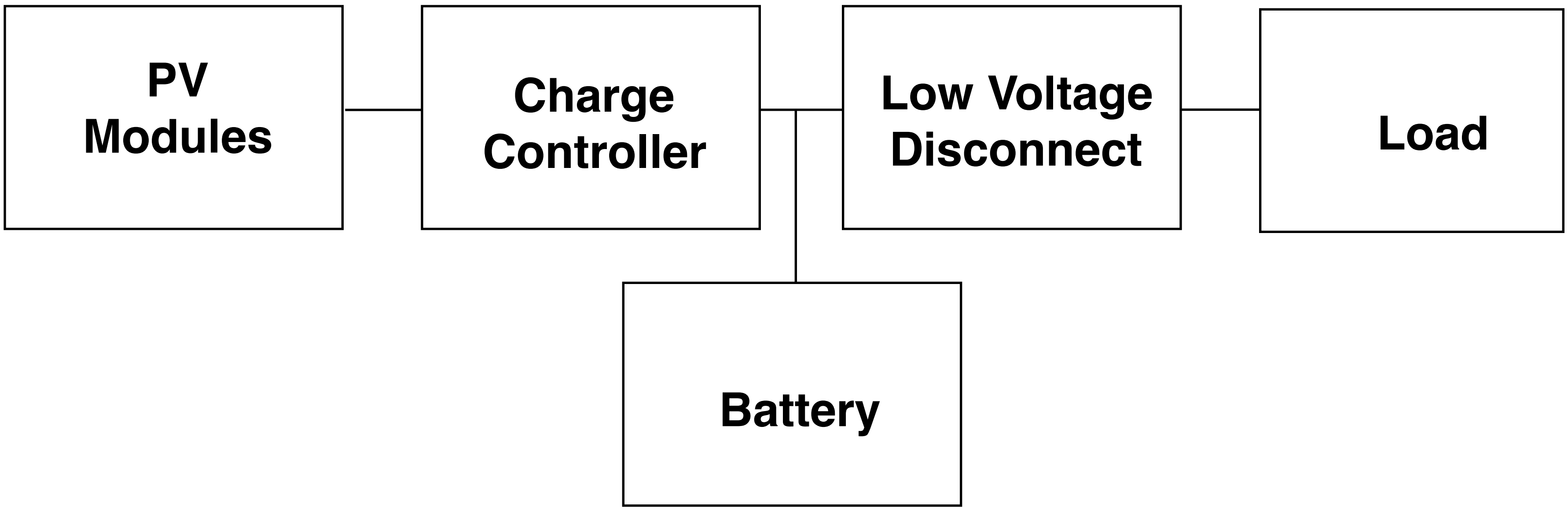
Introduction to PV Systems



Typical Stand-Alone PV System

- Prevents battery overcharging
- Does not control/regulate load voltage
- May fully discharge battery
- DC output

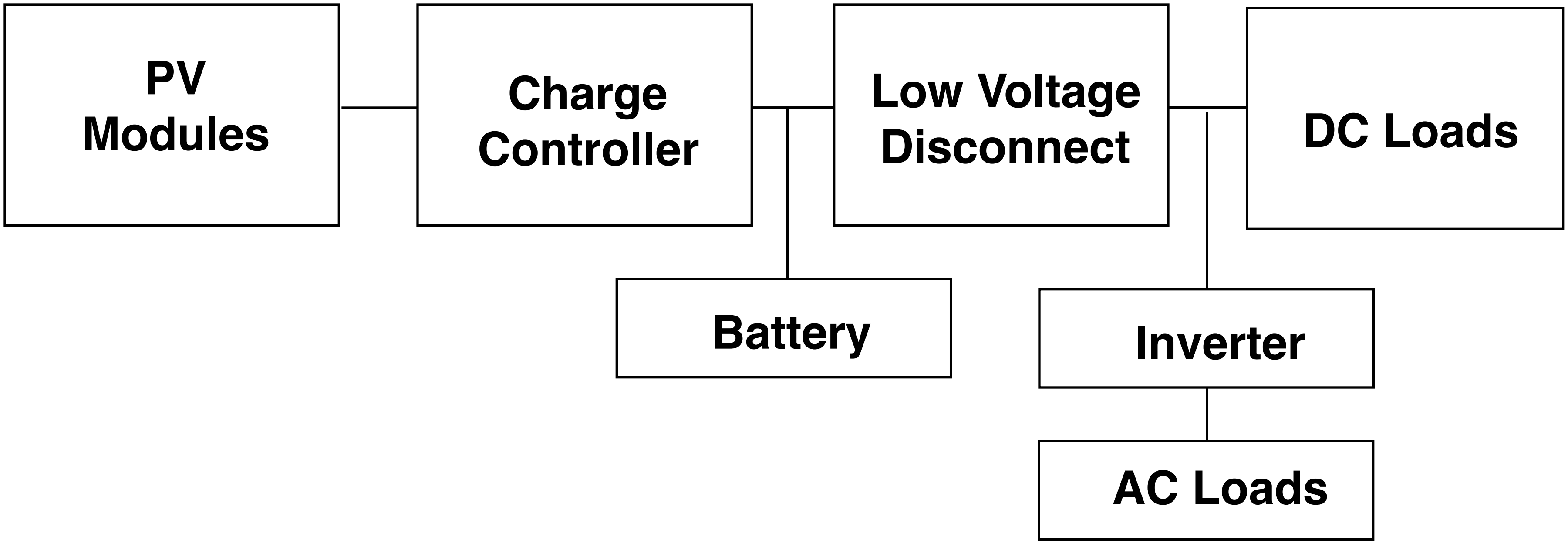
Introduction to PV Systems



Stand-Alone PV System

- Disconnects load at low battery voltage
- DC output

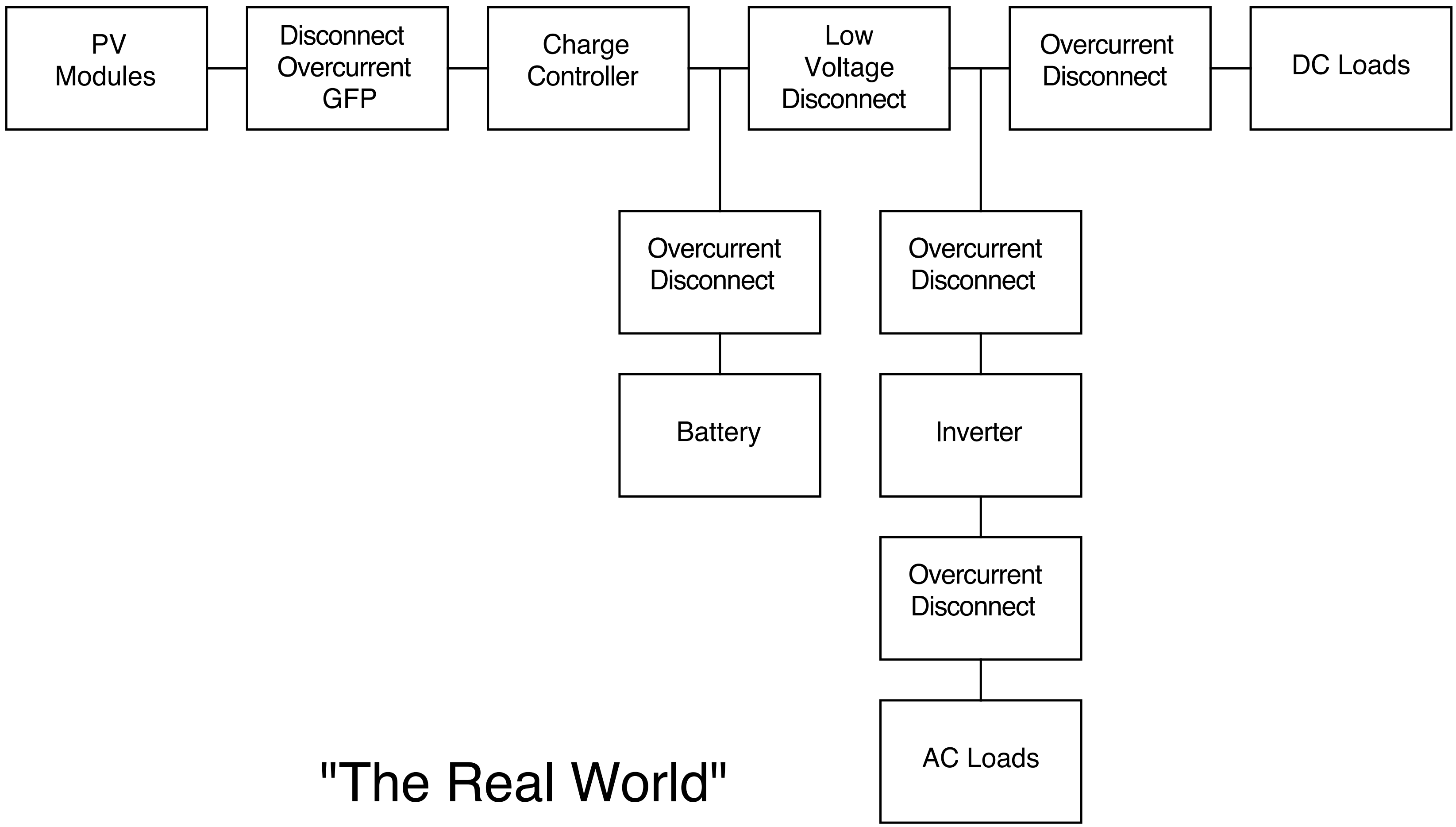
Introduction to PV Systems



Stand-Alone PV System

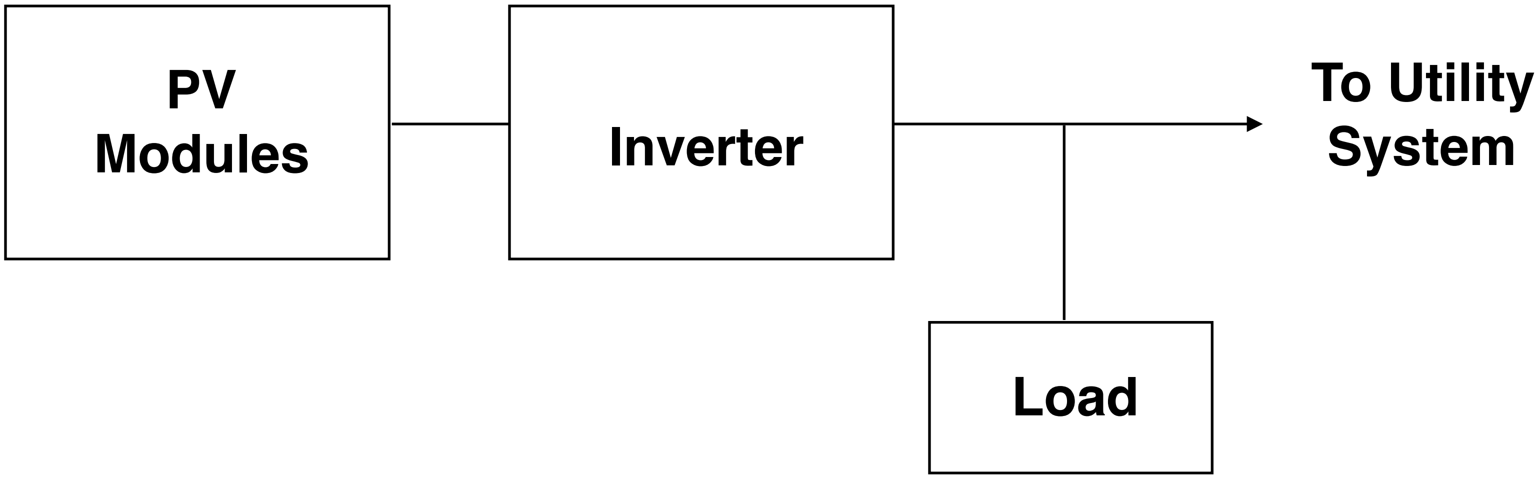
- **AC & DC loads**

Introduction to PV Systems



"The Real World"

Introduction to PV Systems



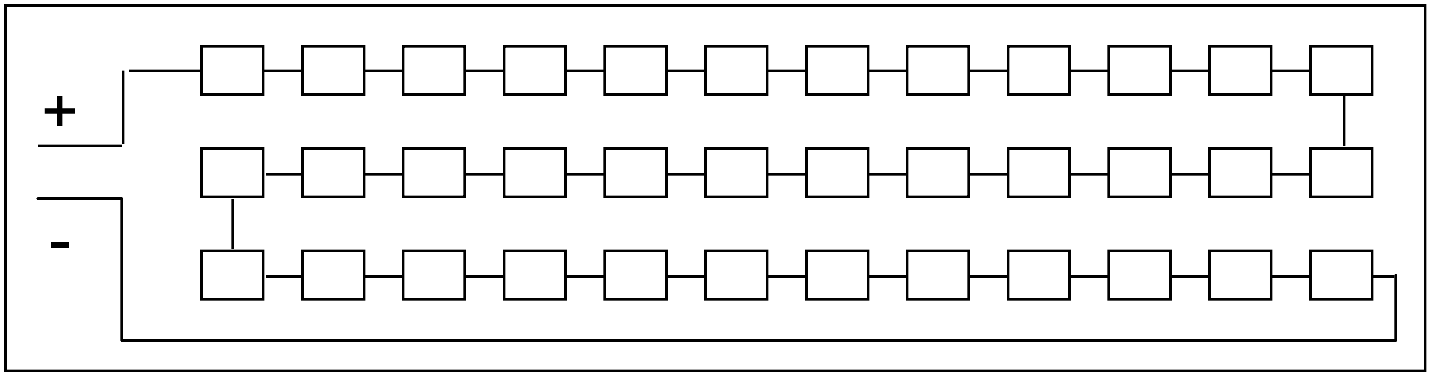
Grid-Connected, Utility-Interactive PV System

- **Relies on Utility for Operation & Storage**

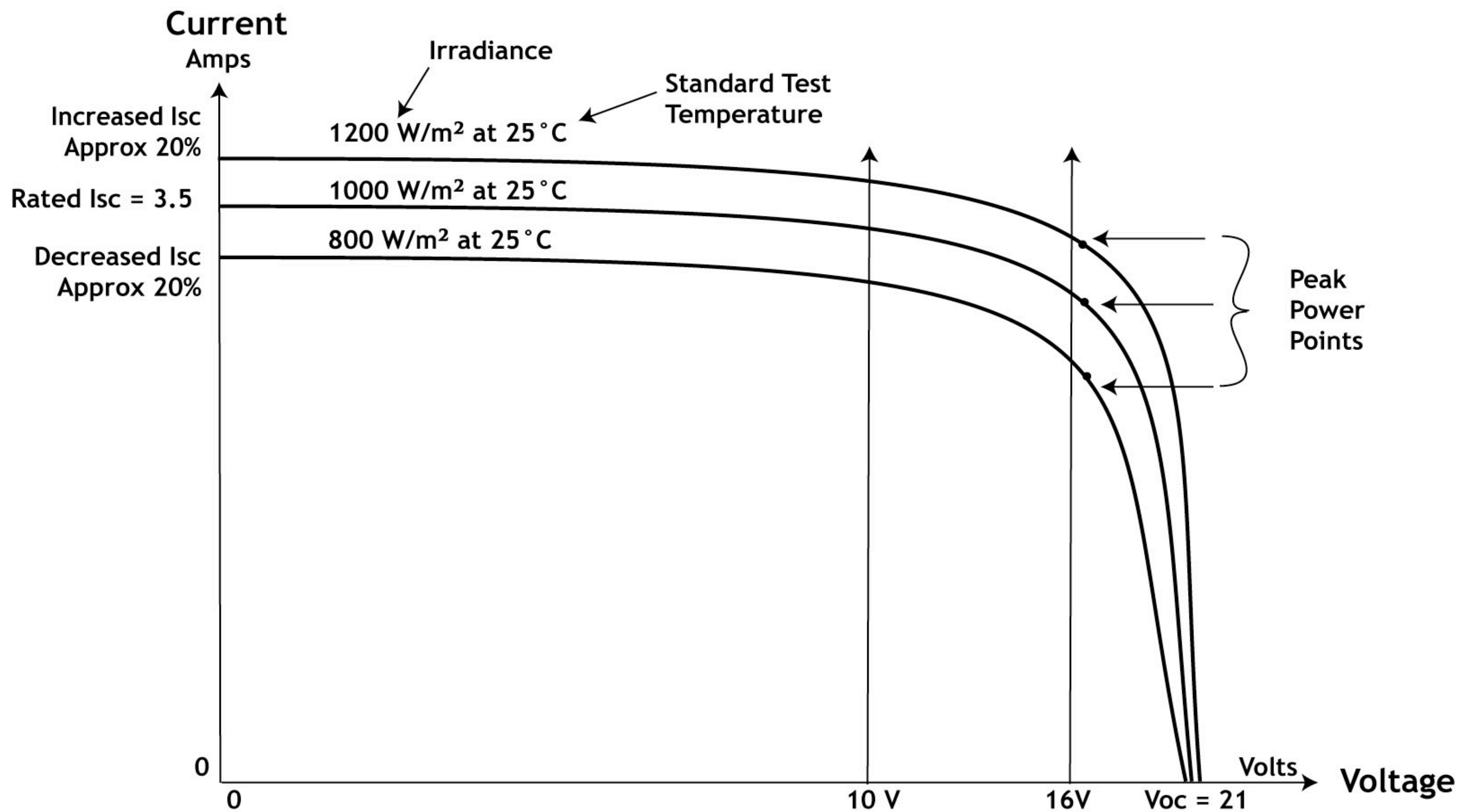
Introduction to PV Systems
The PV Module

- Made up of PV cells connected in series
- PV cell voltage (V_{mp}) about 0.5 V under load
- PV cell current (I_{mp}) 0 up to ~10 A in bright light
- Module (12V) is 30-36 cells connected in series
- Typical 12-volt module - rated at 50-60 W
- Open-circuit voltage (V_{oc}): 18-22 V - even in dim light
- Short-circuit current (I_{sc}): up to ~10 A in bright light
- Can be short-circuited without damage

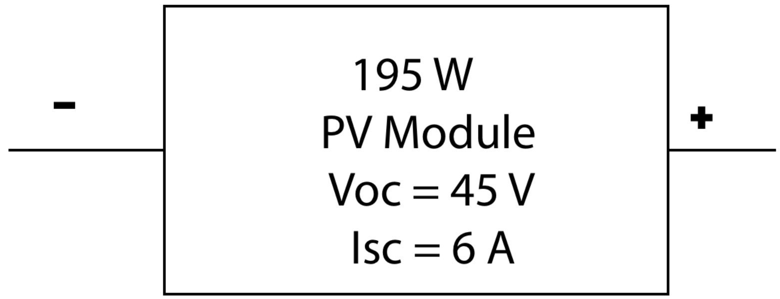
Introduction to PV Systems
The 12-Volt *(24-Volt)* Module

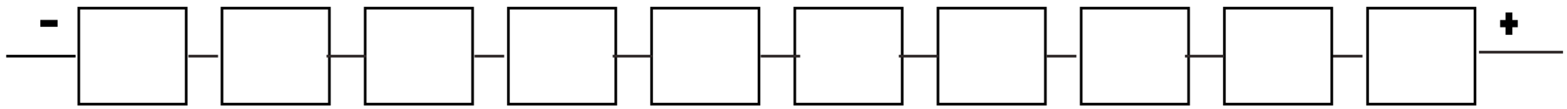


- 36 cells in series *(72 cells in series)*
- 50-60 W output: 17 V & 3 A *(165 W, 34 V, 4.8 A)*
- Open-circuit voltage (V_{oc}): ~22 V *(44 V)*
- Short-circuit current (I_{sc}): ~3.5 A *(5.6 A)*
- Glass front - plastic back (Tedlar) or glass/glass or glass/ aluminum
- Aluminum framed, plastic framed, or unframed laminate



Current
Amps
Irradiance
Standard Test
Temperature
Increased Isc
Approx 20%
1200 W/m² at 25°C
Rated Isc = 3.5
1000 W/m² at 25°C
Decreased Isc
Approx 20%
800 W/m² at 25°C
Peak
Power
Points
0
0
10 V
16V
Voc = 21
Volts
Voltage





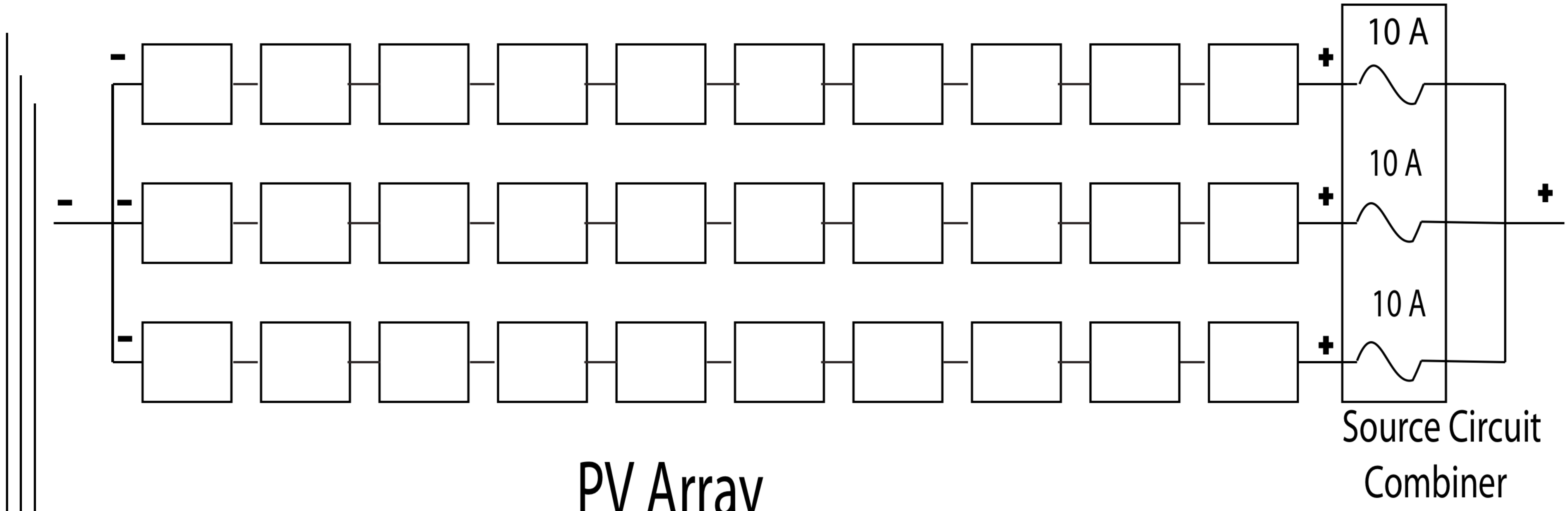
Source Circuit (String)

10 Modules in Series

Voc = 10 x 45 V = 450 V

Isc = 6 A

Power = 10 x 195 W = 1950 W



PV Array

3 Strings In Parallel

Voc = 10 x 45 V = 450 V

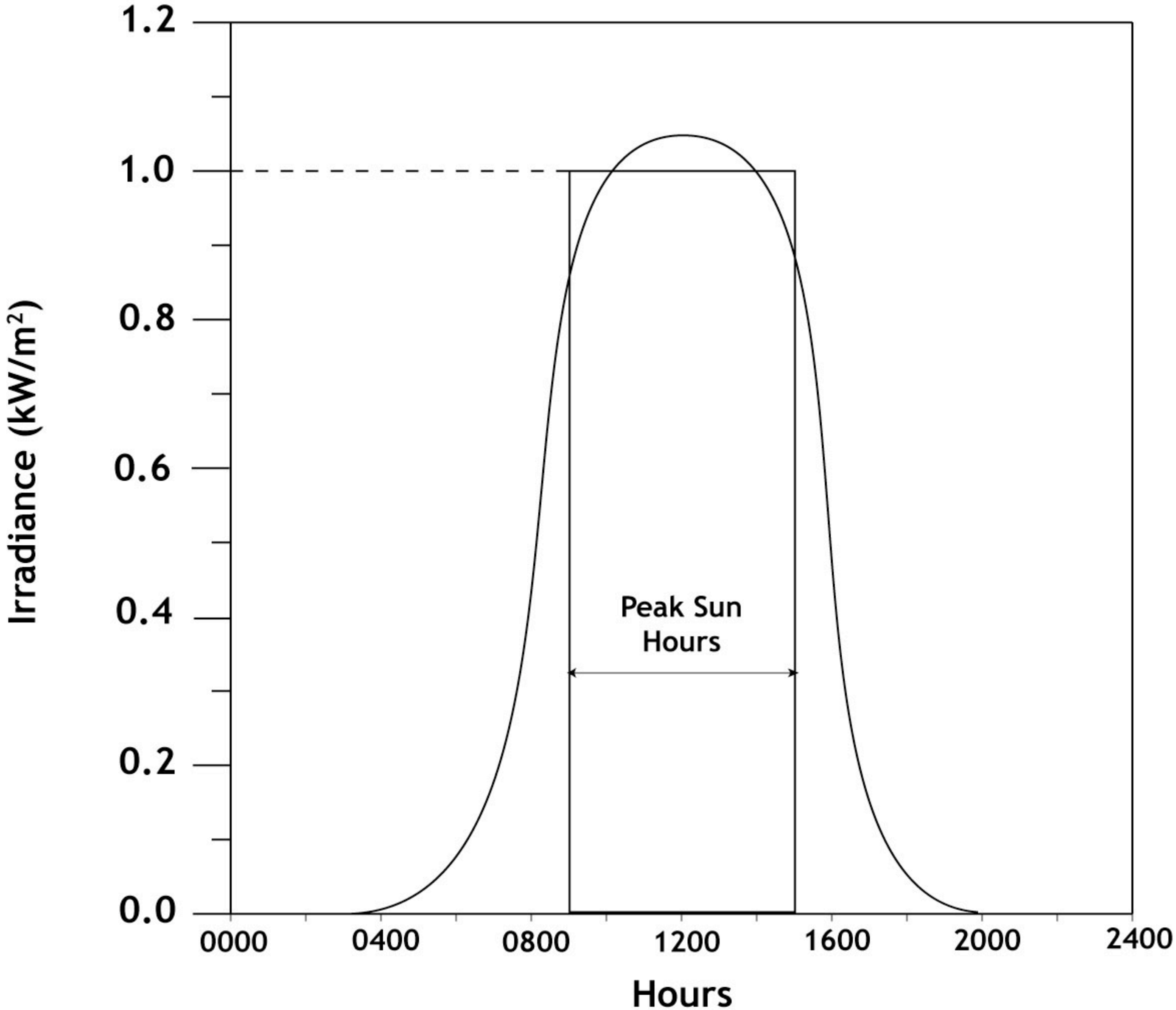
Isc = 3 x 6 A = 18 A

Power = 3 x 1950 W = 5850 W

Introduction to PV Systems
Grid-Tied Systems

- **Series strings of modules operate at 48-600 V.**
- **Each string (source circuit) usually has an overcurrent device where there are three or more strings. A *very few* may have blocking diodes.**
- **Strings are paralleled (sometimes with overcurrent devices) for greater current.**

Peak Sun Hours



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Optimal Photovoltaic Installation

- Direct Sunlight
- 9 am to 3 pm
- No shadows
- Pointed true South (fixed, non tracking array)
- Tilted at latitude above horizon
- Cooler is better

Introduction to PV Systems
Power, Voltage, & Currents

- **Modules**
  - Nominal 12 V and higher DC voltage
  - Connect in series & parallel for higher outputs
  - Current depends on size & sunlight intensity
- **Arrays**
  - Assemblies of modules
  - Provide desired levels of DC voltage & current
- **Charge Controllers**
  - Regulate the state of charge of storage battery
- **Batteries**
  - Store DC power/energy
- **Inverters**
  - Convert DC power to AC power
- **End use appliances/load**
  - Use AC or DC power

The *National Electrical Code* Requirements

Installation Approved by Authority (AHJ)

Equipment Examined for Safety

Listed or Labeled Equipment Required (by AHJ)

- Testing Laboratory with Jurisdictional Authorization—UL, CSA, ETL, and TUV RofA.

Installation Reflects Good Workmanship

PV-Critical Issues in the NEC

- **Section 90.7: Examination of Equipment for Safety.**
  - All equipment in the *Code* shall be examined for safety. Some must be listed. Factory installed wiring internal to listed equipment is not required to be inspected.
- **Section 90.4: Enforcement.**
  - AHJ may waive or establish requirements.
- **Section 110.3: Examination, Identification, Installation, & Use of Equipment.**
  - (B) Installation & Use
    - Listed or labeled equipment shall be used or installed in accordance with any instructions included in the listing or labeling.

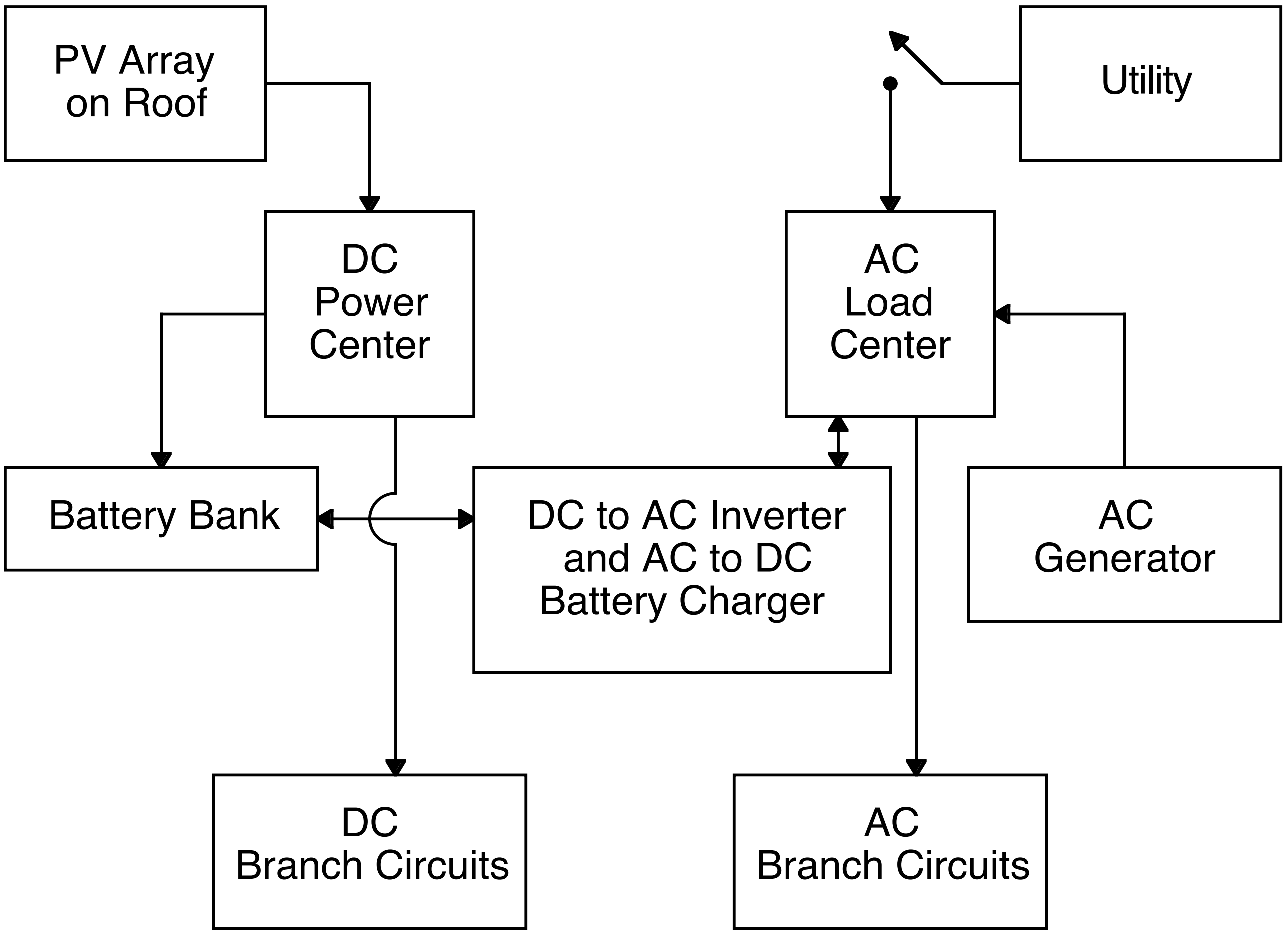
PV-Critical Issues in the NEC

- **Section 110.14: Electrical Connections:**
  - ***(C) Temperature Limitations: Temperature rating associated with ampacity of conductor shall be so selected & coordinated as to not exceed the lowest temperature rating of any connected termination, conductor, or device.***
  - ***Note: Important because PV systems use 90°C conductors and overcurrent devices have terminals rated for only 60°C or 75°C.***

Safety Issues in PV Installations

- **Cable selection and ampacity**
- **Cable overcurrent and short-circuit protection**
- **Component ratings—DC, voltage, current**
- **Operator/User/Servicer safety**

Electrical Power System Diagram



Wiring Methods

Cables for Modules
- **Allowed Methods & Types**

Insulation Materials
- **Environmental Conditions**
- **Terminal Ratings**
- **Fixed or Portable Type Conductors**

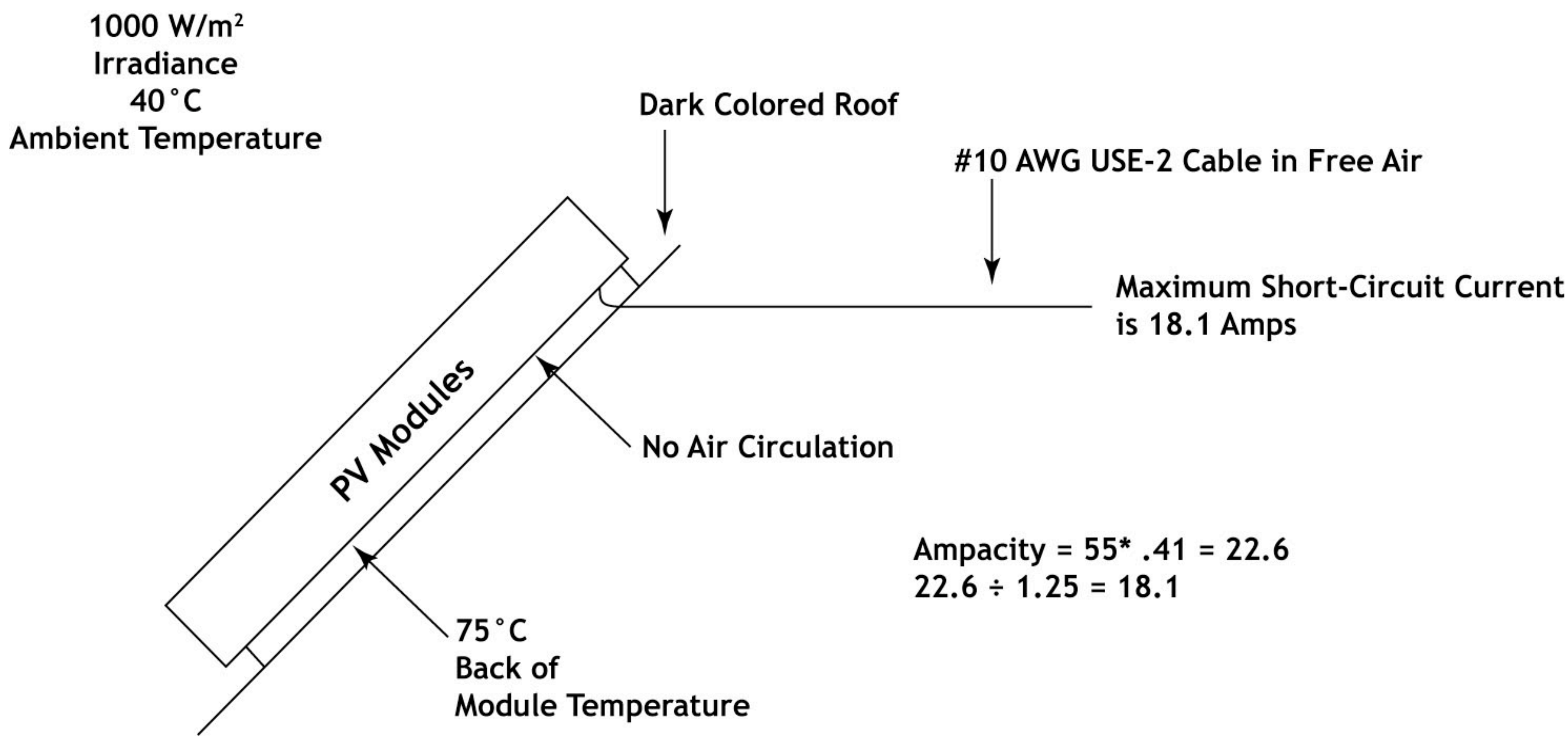
Ampacity Calculations
- **Short-Circuit Currents**
- **Enhanced Irradiance**
- **Temperature Derating**

Connections

PV & *NEC* Module Cable Ampacity & Overcurrent Device Rating

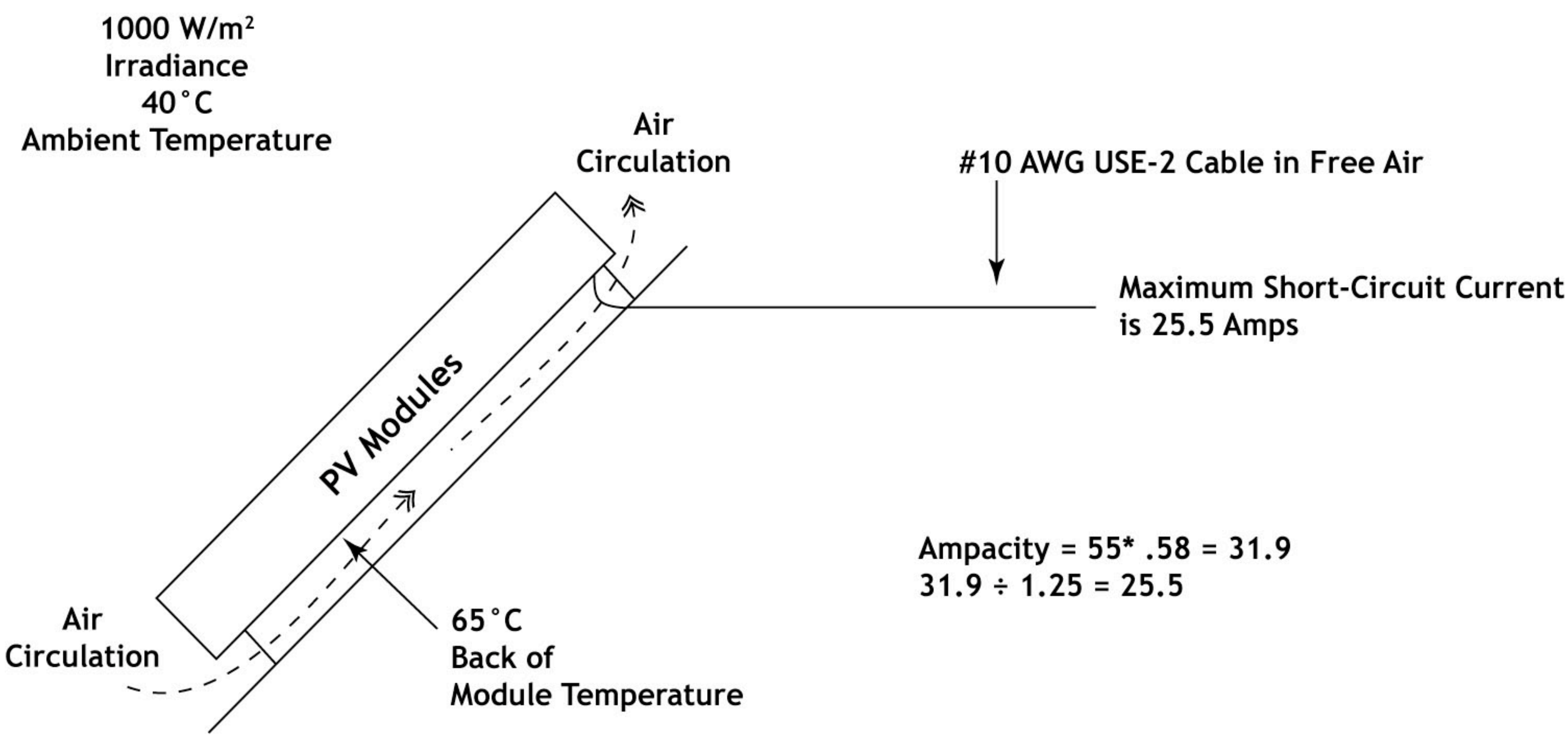
- **Modules are rated by UL at 1000 W/m^2 & 25°C (Standard Test Conditions-STC)**
- **Modules operate 0-1500 W/m^2 & -50 to +80°C**
- **Module short-circuit current (I_{sc}) is direct function of sun**
- **Module open-circuit voltage (V_{oc}) is inverse function of temperature**
- **UL requires I_{sc} to be multiplied by 125% (before *NEC* Calculations)**
  (Now also in NEC 690.8(A)(1))
- **UL requires V_{oc} to be multiplied by 125% (before *NEC* Calculations)**
  (Now as a temperature-dependent factor in NEC 690.7)
- ***NEC* requires I_{sc} to be multiplied by second 125% (690.8(B))**
- ***NEC* requires system voltage to be highest dc voltage in system**

Effects of Temperature on Conductor Ampacity



Ampacity = 55* .41 = 22.6
22.6 ÷ 1.25 = 18.1

Effects of Temperature on Conductor Ampacity



PV & *NEC*
Module Cable Ampacity & Overcurrent Device Rating

- Typical 24 V module: V_{oc} = 44 V, I_{sc} = 5.3 A, Power = 200 W
- 125% Voc = 55 V 125% I_{sc} = 6.6 A (continuous currents) 1.25 x 6.6 = 8.3 A
- Module interconnecting cable must have ampacity of 6.6 A (cont current)
- Overcurrent device must be rated at or above 8.3 A (1.56 Isc) but less than cable ampacity — Therefore the cable rated at 8.3 A or better
- Voltage rating of cable & overcurrent device must be 55 V DC or greater

PV & *NEC* Module Cable Selection

- Single-Conductor USE-2, *SE*, & *UF* cables are allowed
- Conduit & other wiring methods are acceptable
- All exposed cables must be sunlight resistant
- 90°C cable is required
- Ampacity must be derated for conditions of use
  - Temperature and Conduit Fill
- Exposed or buried conduit requires wet-rated conductors (USE-2, XHHW-2, RHW-2, THWN-2)

PV & *NEC*
Module Cable Temperature Derating

- USE-2 Number 10 AWG has ampacity of 55 A in free air at 30°C [*NEC* Table 310.17]

  - At 65°C, ampacity is 31.9 A (55 x 0.58)(max fuse 30 A) (vented location)

- RHW-2 Number 10 AWG has ampacity of 40 A in conduit at 30°C [*NEC* Table 310.16]

  - At 75°C, ampacity is 16.4 A (40 x 0.41) (non vented location)

- Conductor ampacity after corrections must be equal to or greater than 1.25 I_{sc} (continuous current)
- Conductor ampacity at 30°C must be equal to or greater than 1.56 I_{sc} (1.25 x continuous current)
- Overcurrent Device at 1.56 I_{sc} must protect the conductor

Wiring Methods—Modules

- Methods & Types
  - Single Conductor USE-2, *UF, SE* Cables *(“PV Wire”)*
  - Sheathed Cables, Cables in Conduit
  - Solid, Stranded, Flexible—Portable cords OK for Trackers
- Ampacity Calculations
  - 125% I_{sc}—Twice
  - Temperature derating (Table 310.16, 310.17)
  - Terminal temperature limits
- Insulation
  - Temperature Range—90°C
  - Sunlight resistant (exposed)/wet-rated
  - Color (white or gray for grounded conductor; green, green/ yellow, or bare for equipment grounding)
- Connections
  - Pressure, crimped, soldered *(Fine-stranded cable limitations)*

Conductor Sizing & Overcurrent Device Rating

- Determine continuous current (1.25 I_{sc})
- Calculate 1.25 x continuous current (1.56 I_{sc})
- Select conductor and overcurrent device
- Evaluate conductor ampacity under conditions of use (temperature, conduit fill)
- Evaluate at Terminal Temperatures (each terminal)
- Ensure overcurrent device protects selected conductor under conditions of use

Table 310.16 COPPER AWG or kcmil	Ampacities of conductors in conduit at 30°C (86°F) Temperature Rating of Conductor (See Table 310.13)		
	60°C (140°F)	75°C (167°F)	90°C (194°F)
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	RHH, THHN, THHW, THW-2, THWN-2, USE-2 XHH, XHHW, XHHW-2
	COPPER		
14*	20	20	25
12*	25	25	30
10*	30	35	40
8	40	50	55
6	55	65	75
4	70	85	95
3	85	100	110
2	95	115	130
1	110	130	150

CORRECTION FACTORS

Ambient Temp°C	Ambient temperatures other than 30°C (86°F), multiply by the factor shown.		
21-25	1.08	1.05	1.04
26-30	1.00	1.00	1.00
31-35	0.91	0.94	0.96
36-40	0.82	0.88	0.91
41-45	0.71	0.82	0.87
46-50	0.58	0.75	0.82
51-55	0.41	0.67	0.76
56-60	—	0.58	0.71
61-70	—	0.33	0.58
71-80	—	—	0.41

Table 310.17	Ampacities of conductors in free air at 30°C (86°F) Temperature Rating of conductor (See Table 310.13)		
	60°C (140°F)	75°C (167°F)	90°C (194°F)
COPPER AWG or kcmil	TW, UF	RHW, THHW, THW, THWN, XHHW	THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2
14*	25	30	35
12*	30	35	40
10*	40	50	55
8	60	70	80
6	80	95	105
4	105	125	140
3	120	145	165
2	140	170	190
1	165	195	220
Correction Factors			
Ambient Temp °C	Ambient temperatures other than 30°C (86°F), multiply by the factor shown.		
21-25	1.08	1.05	1.04
26-30	1.00	1.00	1.00
31-35	0.91	0.94	0.96
36-40	0.82	0.88	0.91
41-45	0.71	0.82	0.87
46-50	0.58	0.75	0.82
51-55	0.41	0.67	0.76
56-60		0.58	0.71
61-70		0.33	0.58
71-80			0.41

Terminal Temperature Limits 110.14(C)

Use terminal temperatures marked on equipment

No Markings:

- Circuits 100A or less or 14-1 AWG, use 60 deg C limit
- Circuits over 100A or greater than 1 AWG, use 75 deg C limit

Use Table 310.16

- For conductor size selected, Read 60 deg C or 75 deg C Current
- This Current must be greater than or equal to 1.25 continuous current.

Wiring Methods

Module Wiring Example - Number 1

Combined Output of Six Sharp 208 W Modules in Parallel
Wiring (after combiner) in conduit routed behind modules

I_{sc} = 6 x 8.13 A = 48.78 A V_{oc} = 36.1V
125% x I_{sc} = 1.25 x 48.78 = 60.975 A (continuous current)
125% x 60.975 = 76.2 A (overcurrent device) >> 80 amps
Combiner Terminals Marked at 75°C, Fuse Terminals marked 60°C
Estimated Back-of-Module Temperature—60 - 69°C

With 76.2 A minimum fuse, select No. 2 AWG USE-2/RHW-2 (90°C column)

From Table 310.16, ampacity is 130 A x .58 temp derate factor = 75.4 A

This is greater than continuous current of 61 A—ok

Can be protected by a 80 amp fuse (240.4)—ok

Terminal Temperature Check

With 60°C insulation, No. 2 AWG cable has 30°C ampacity = 95 A *(Table 310.16)*

This is greater than 76.2 A (125% continuous currents)—ok.

Note: Conductors in conduit in sunlight operate 17-20°C above max ambient

2005 NEC FPN #2, 310.10 (+14 to +33°C in 2008 NEC—310.15(B)(2))

Wiring Methods

Module Wiring Example - Number 2

Large Direct Roof-Mount PV Module, Cables in Free Air

I_{sc} = 19 A, V_{oc} = 22 V

Module Terminals Rated at 90°C, Circuit Breaker (CB) rated at 75°C

Back-of-Module Temperature 60 - 68°C

125% I_{sc} = 23.75 A—continuous current

125% x 23.75 = 29.7 A (required overcurrent device) (round up to 30 A)

From Table 310-17, select No. 12 AWG USE-2/RHW-2 cable. (90°C Column)

Derated ampacity is 40 x 0.58 = 23.2 A *(can use 25 A CB)*

Derated ampacity is less than 23.75 A continuous current—*No Good*

25 A allowed CB is less than 30 A Required CB *No Good*

Check No. 10 AWG USE-2/RHW-2 cable

Derated ampacity is 55 x 0.58 = 31.9 (OK for 30 A fuse)—OK

Derated ampacity is greater than 23.75 A continuous current—OK

Terminal Temperature Check-310.16

With 75°C insulation, No. 10 AWG: 35 A, greater than 29.7 A—OK

Module Wiring

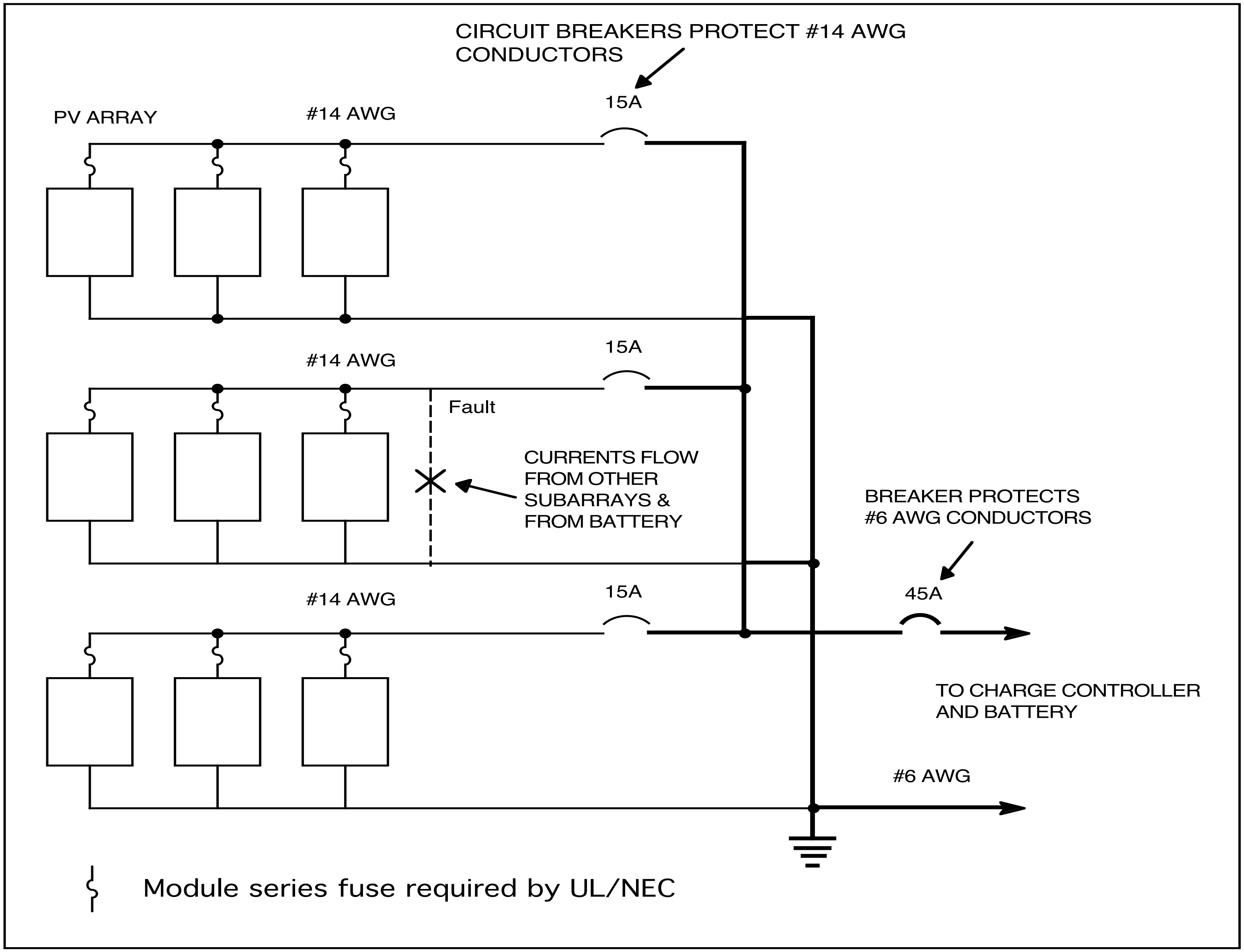
- **Any method approved by *NEC*** (690.31, CH 3)
- **Single conductor, USE-2 & *PV Wire* (690.31) *2008 NEC***
- **Ampacity—insulation, temperature, installation, terminals** (310, 110.3)
- **Ampacity: Based on I_{sc}, 125% for normal operation, 125% *NEC* continuous currents** (690.8, UL)
- **Strain relief** (690.32)
- **Color coding** (310.12, 200.6(A) (2))
- **Grounding** (690.41, 42, 43, 45, 47, 250)

PV Modules

- **Marking** (690.51) **- Also UL-1703**
  - Polarity
  - Maximum Overcurrent Device (reverse current protection)
  - Rated Open-circuit Voltage, Operating Voltage, Maximum System Voltage, Operating Current, Short-circuit Current, Maximum Power
- **Connections** (690.33,34)
  - Concealed connectors and fittings
  - Polarized, guarded, latching, grounding, load-break rated
  - Access to Junction Boxes—Removable fasteners, flexible wiring

PV Modules

- **Junction/Combiner Box** (690.32, 300.15, 408)
- **Metallic Frames—Grounded Directly** (690.43,45**)**
- ***PV Source Circuits must remain outside building until first disconnect unless in metallic raceways (690.14, 31(E)—2005 NEC)***
- **Up to 600 V—1 and 2-family dwellings—V_{oc}** (690.7(C,D))
- **Above 600 V on other than 1 and 2-family dwellings**
  —See 690 Part IX



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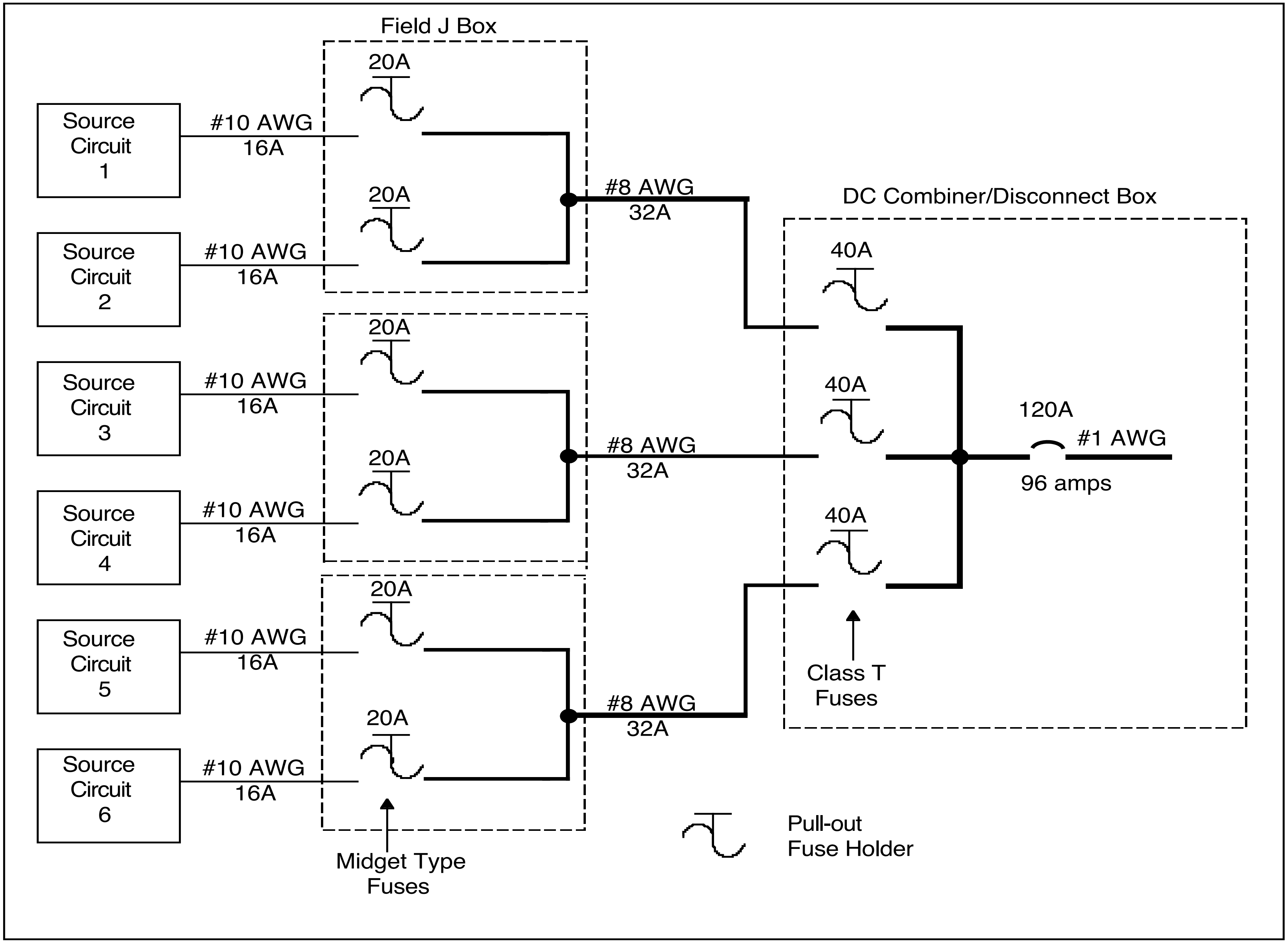

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Selecting Overcurrent Devices and Conductors in PV Systems

1. Define Continuous Currents

The unique nature of PV power generators dictate that all ac and dc calculated currents are continuous and are based on the worst-case conditions. There are no non-continuous currents.

A. DC currents in PV source and output circuits are 125% of the short-circuit current (I_{sc}) (690.8(A)(1)).

B. AC inverter (stand-alone or utility interactive) output currents are at the rated output of the inverter (690.8(A)(3)).

C. DC Inverter input currents from batteries are at the rated output power of the inverter at the lowest battery voltage that can maintain that output (690-8(A)(4)).

Selecting Overcurrent Devices and Conductors in PV Systems (continued)

2. Select Overcurrent Device

A. Rated at 125% of continuous current (690.8(B)(1)).

1. If listed in enclosure for 100% duty, then use 100% continuous current (690.8(B)(1) EX))—Typically circuit breakers only

2. May round up to next standard rating (<=800A)(240.4(B). PV circuits 1-15 A in 1 A increments (690.9(C)). *1-10, 12, 15A*

B. If overcurrent device is exposed to temperatures (operating conditions) greater than 40°C, must use temperature correction factors on the device rating (110.3(B)). Manufacturer's data

Selecting Overcurrent Devices and Conductors in PV Systems (continued)

3. Select Conductor

A. Select conductor with ampacity (at 30°C) **greater than or equal to** 125% of continuous current (215.2(A)(1)).

B. Conductor selected must have ampacity after corrections for conditions of use (ambient temperature and conduit fill) **greater than or equal to** continuous currents *(no 125%).*

(1) Apply at all points of different temperatures and/or conduit fill.

(2) Use 10%/10-foot rule where appropriate (310.15(A)(2) EX)

C. Select largest conductor from 3.A. or 3.B (310.15(A)(2))

Selecting Overcurrent Devices and Conductors in PV Systems (continued)

4. Evaluate conductor temperature at each termination

A. Find current for conductor size selected in 3.C from Table *310-16*, 60°C or 75°C table depending on conductor temperature limitation of device terminals (110.14(C)).

B. Current must **greater than or equal to** ***1.25*** continuous current.

C. Increase conductor size, if necessary, to meet 4.B. at all terminations.

Note: This step may be combined with 3A.

Selecting Overcurrent Devices and Conductors in PV Systems (continued)

5. Verify That Overcurrent Device Protects Conductors

A. The rating (after any corrections for conditions of use—2.B.) of the overcurrent device selected in 2. **Must be less than or equal to** the ampacity of the conductor selected in 4.C. The ampacity used must be corrected for the conditions of use (3). Rating round-up is allowed (240.4(B))

B. Increase conductor size if not protected by the overcurrent device.

Ground-Fault Protection Device
NEC 690.5

- **Roof mounted PV arrays on dwellings (all systems in *2008 NEC*)**
- **Reduce fire hazard**
- ***Detect fault***
- ***Interrupt fault current***
- ***Indicate the fault***
- ***Disconnect the array or turn off the equipment***
- **Built in to most utility-interactive inverters** (fuse on bottom)
- **Listed equipment available for stand-alone systems**

Overcurrent Devices

- **DC Rated (in DC Circuits), Listed/Certified to UL Standards**

- **PV Source Circuits to Inverter or Battery**
  - Listed Supplementary Fuses (Midget or Ceramic Type)
  - Listed Supplementary Circuit Protectors
  - The use of branch-circuit rated devices is preferred

- **Battery to Load (Inverters and other dc loads)**
  - Listed Branch-Circuit Rated
    - Class Type Fuses
    - Branch-Circuit rated Circuit Breakers

- **Current rating: 125% of Steady-State Currents (**unless 100% rated**)**

- **Voltage Rating: System V_{oc} x (Temperature Dependent Factor—690.7)**
  - Battery Circuits—Highest Equalization Voltage

Disconnect Devices

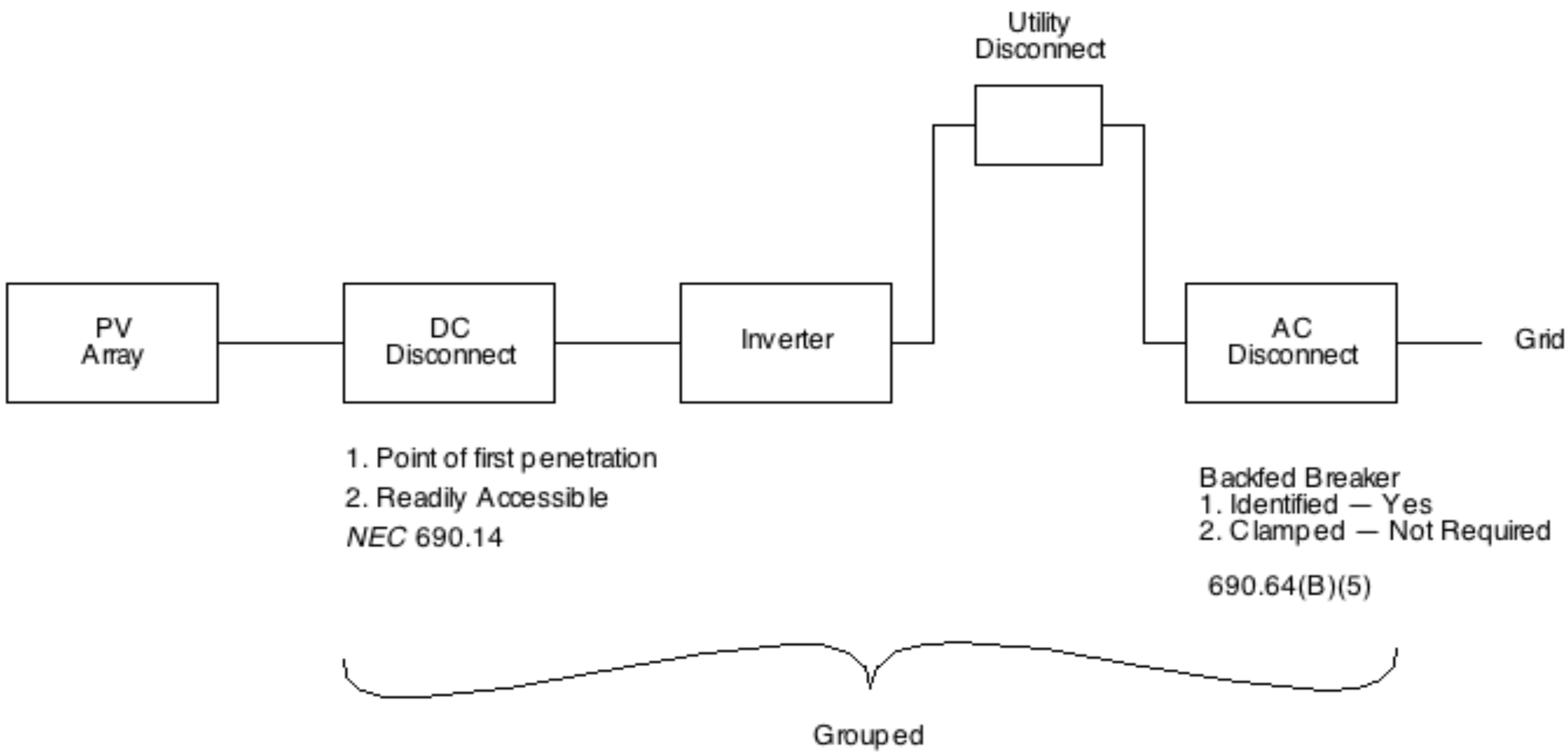
- **DC Rated (in DC Circuits), Listed/Certified to UL Standards**
- **Circuit Breakers**
  - With and without current trips
- **Switches**
  - Load break and non-load-break operation (restricted)
  - Pull out or lever type
- **Bolted Connections for Grounded Conductors**

  Never switch a grounded conductor
- **Voltage Rating: System V_{oc} x (Temperature Dependent Factor—690.7)**
  - Battery Circuits—Highest Equalization Voltage

PV Disconnect History

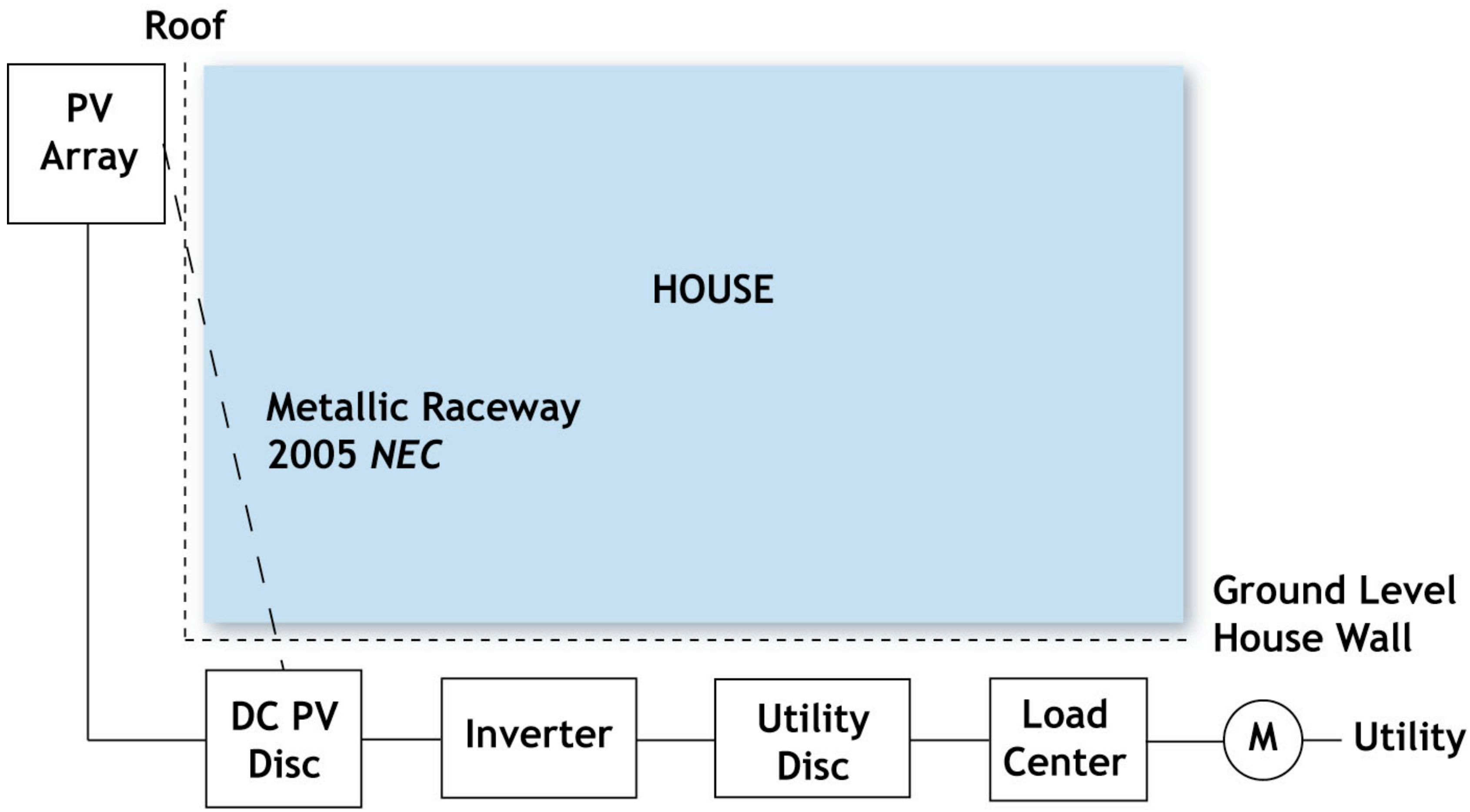
- **Prior to 1984—PV from the start should comply with *NEC***
- **1984—Article 690 added to *NEC***
  - – Main PV Disconnect (690.14) —> 230 Part F
    - Treat same as AC service disconnect
- **2002—NFPA rewrote 690.14**
  - – Keep the PV circuits outside building to the PV Disco
- **2005—Use of metallic raceways OK'd in building**
- **Will Fire Departments have any future impact?**

Utility Interconnected PV
The Big Picture

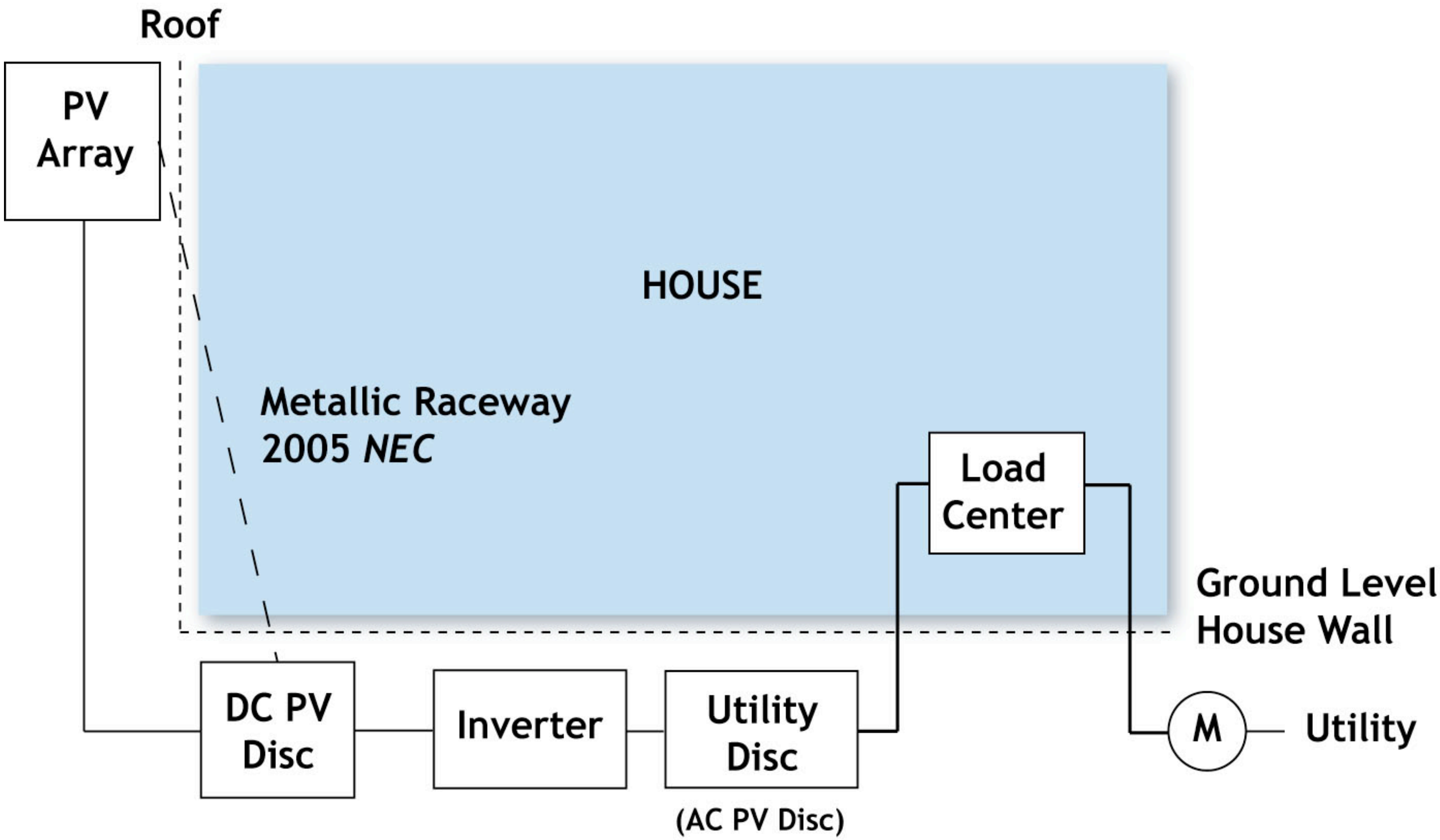


SB-1

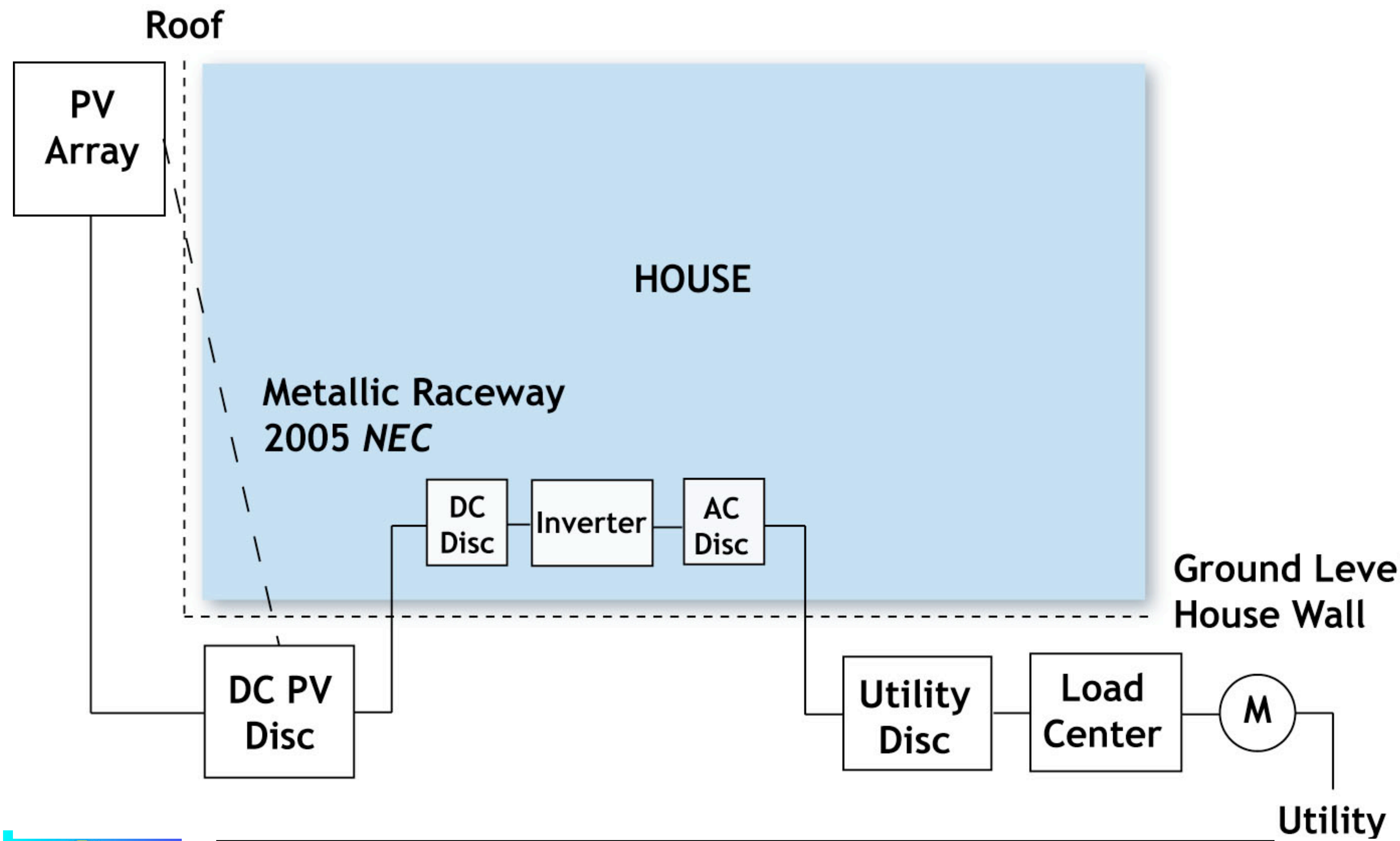
Disconnect Locations
Utility Interactive System

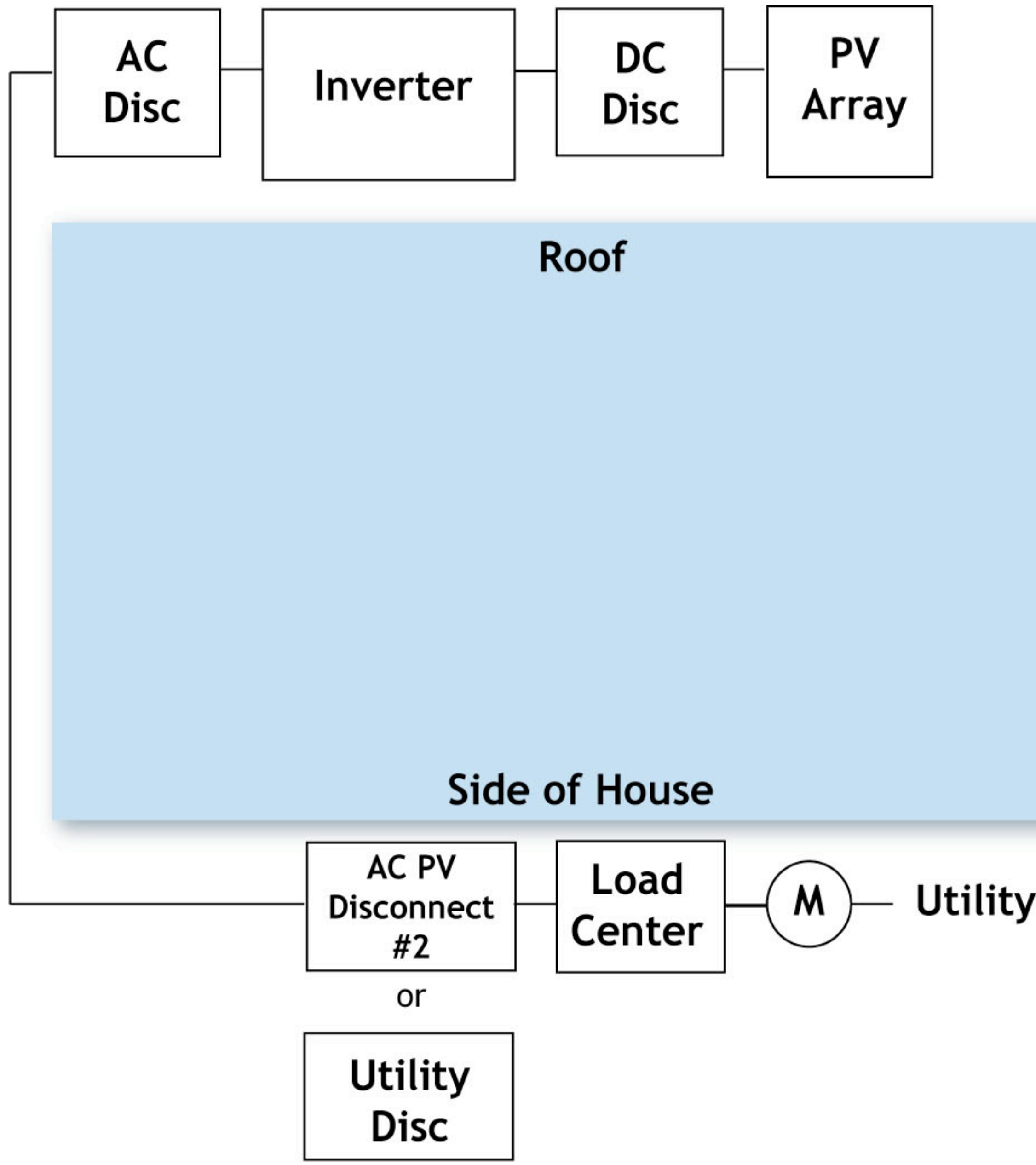


Disconnect Locations
Utility Interactive System



Disconnect Locations
Utility Interactive System





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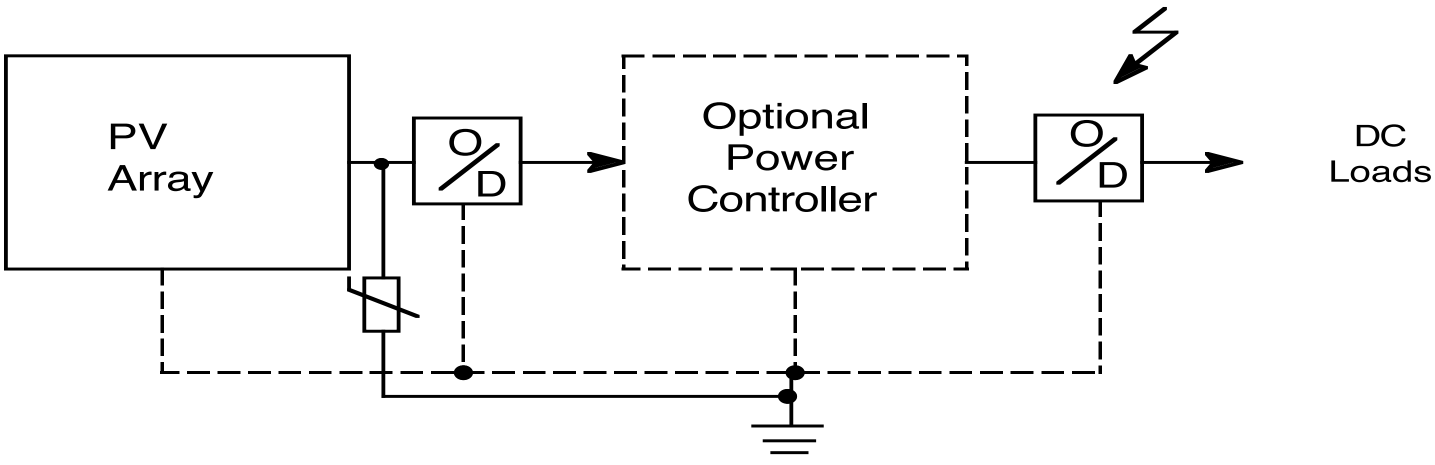
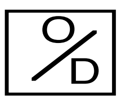
Direct Connected System - DC, No Battery

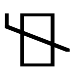


Notes: Block Diagram
Typical O/D Locations



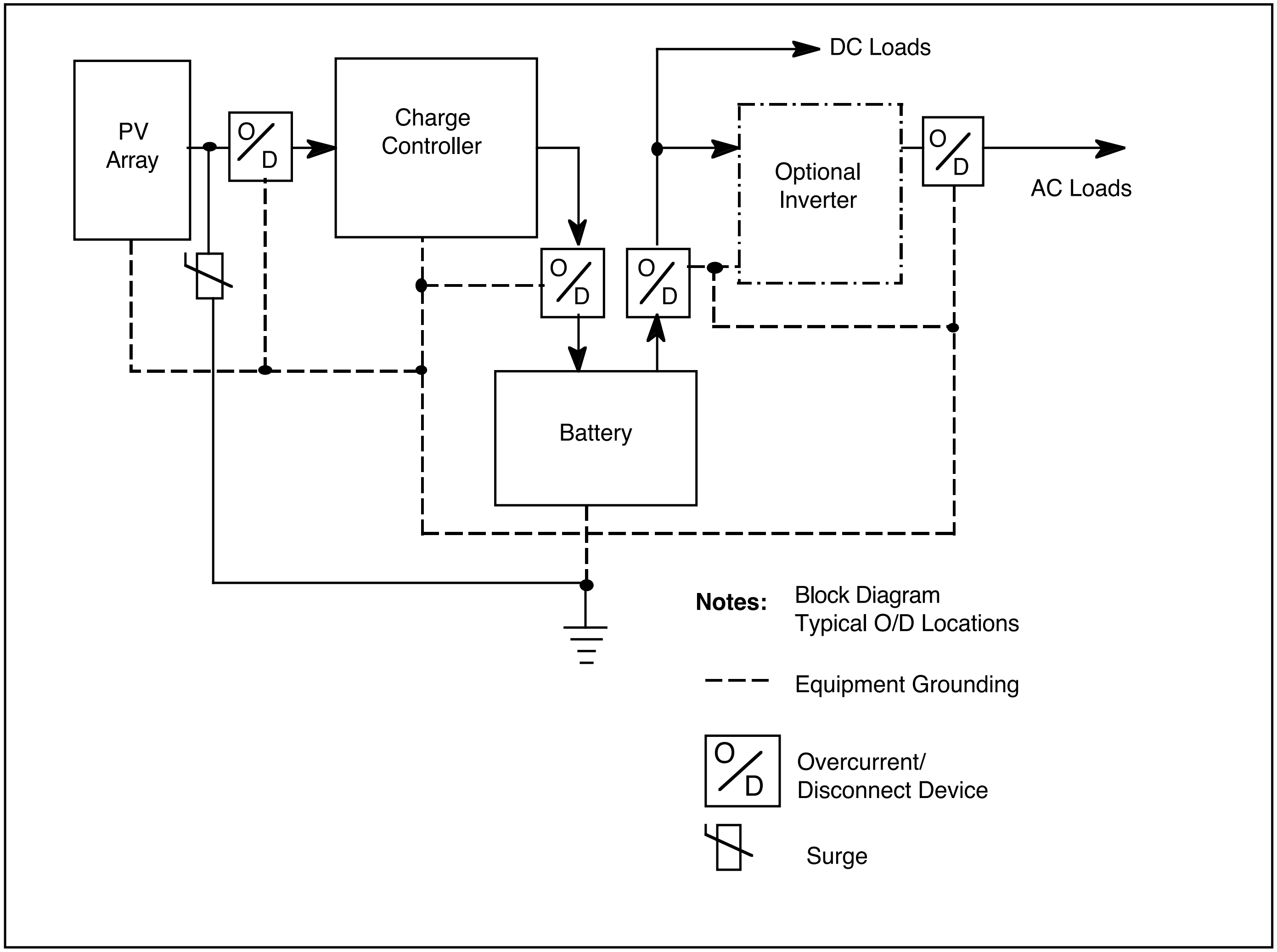
Overcurrent/
Disconnect Device

---- Equipment Grounding

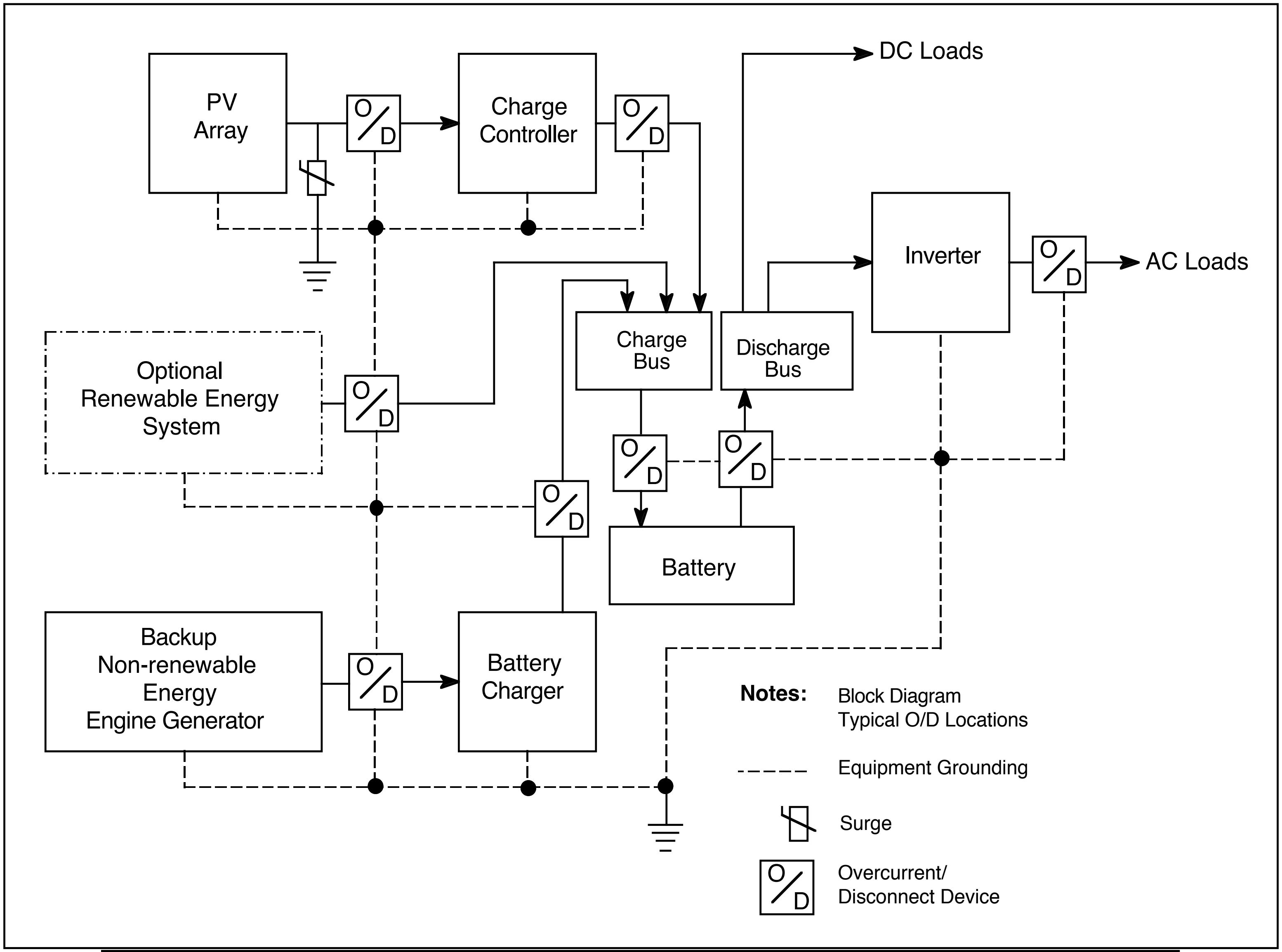


Surge Suppressor

Stand-Alone System (AC Output Optional)



Stand-Alone System - Hybrid with Batteries



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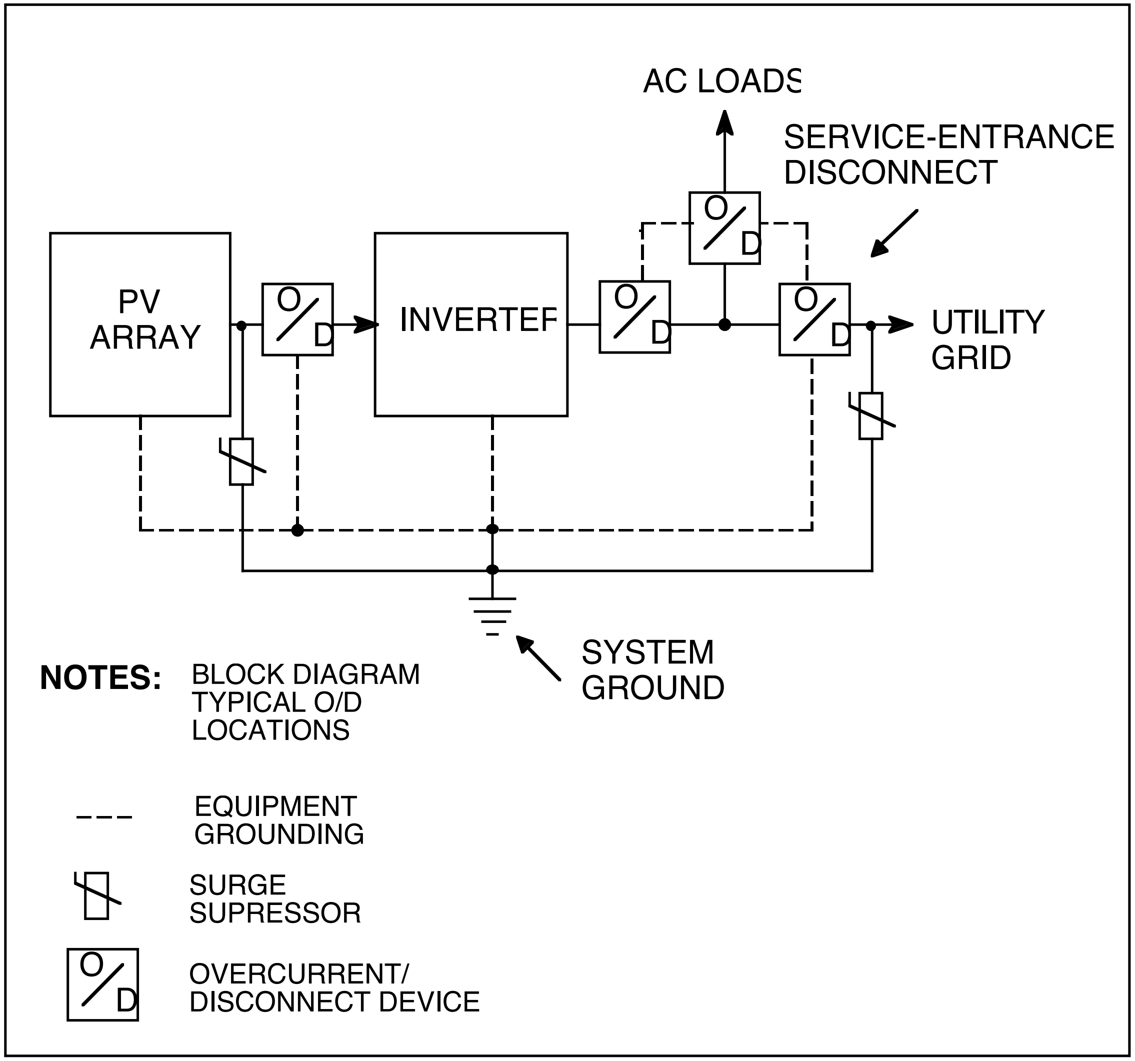
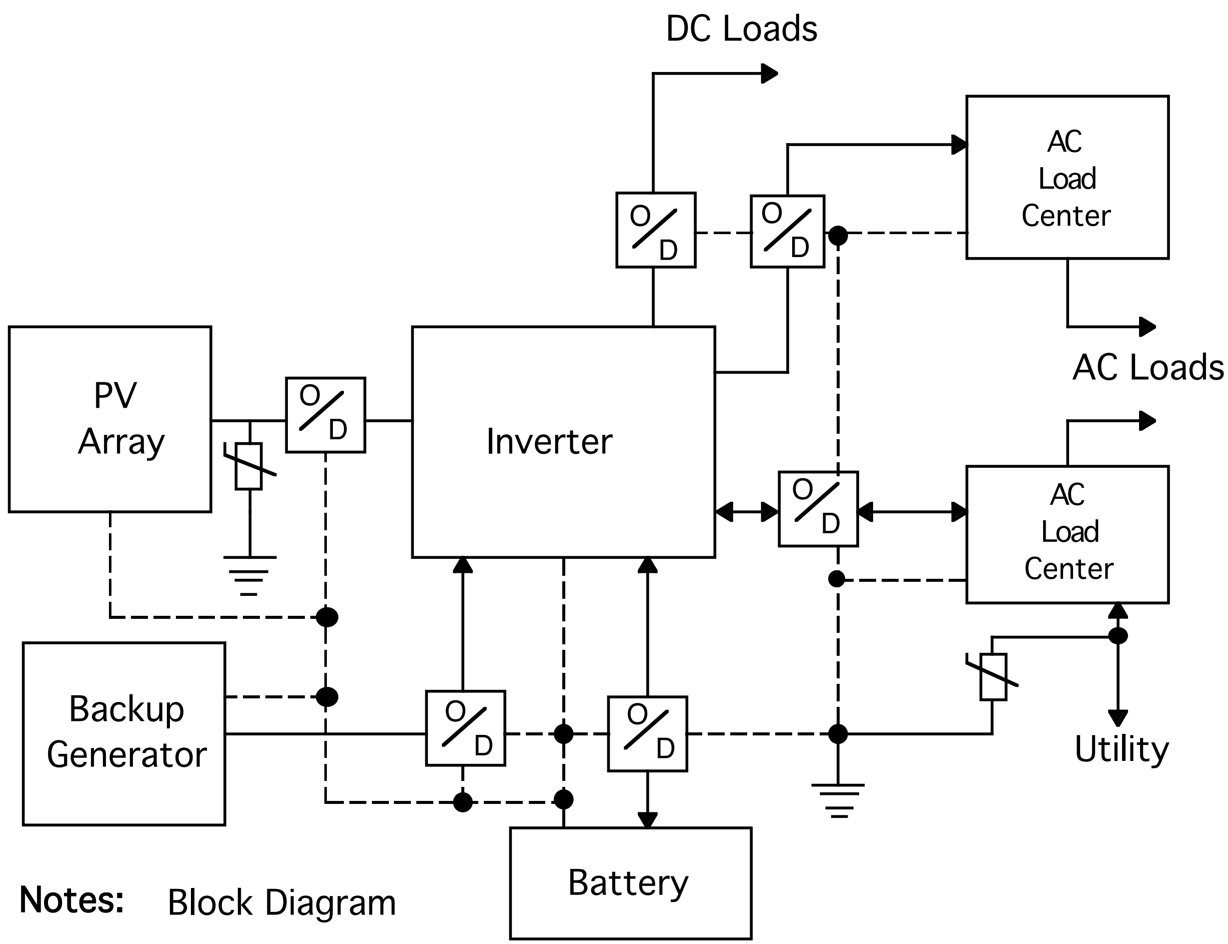
Grid-Tied System



Stand-Alone and Grid-Connected System

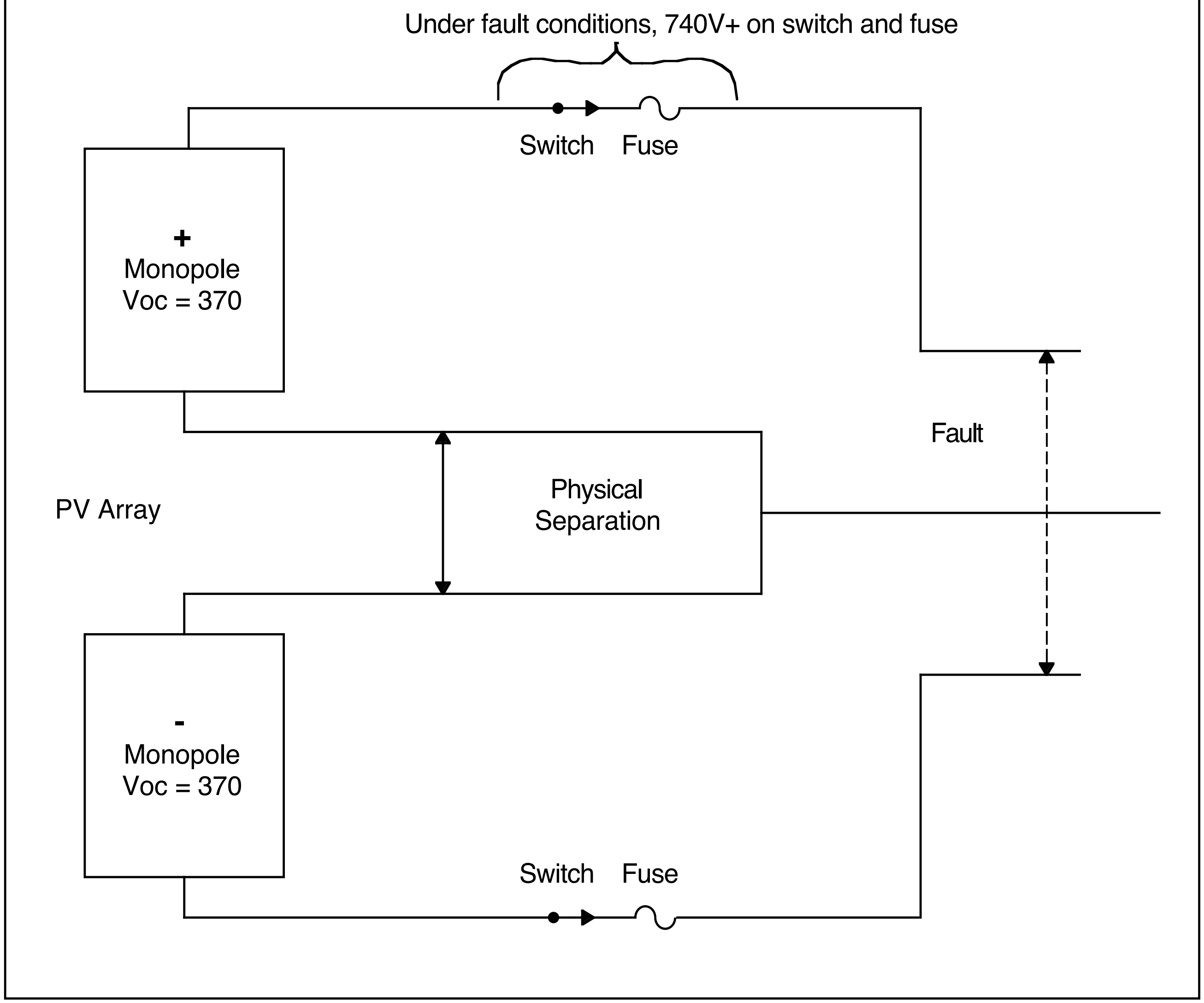


Notes: Block Diagram

- - - - - Equipment Ground

O/D Overcurrent/ Disconnect Device

Fault Analysis



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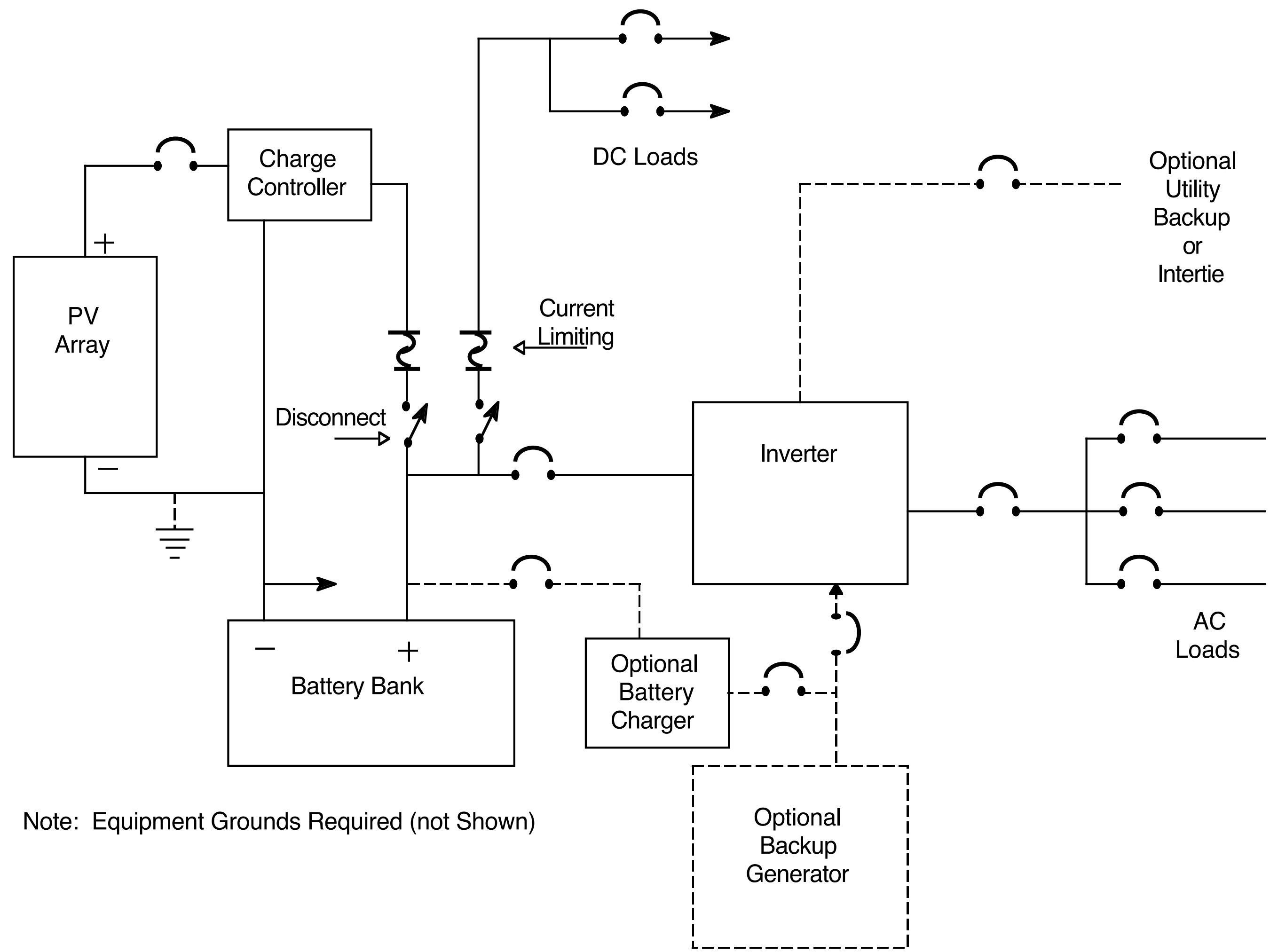
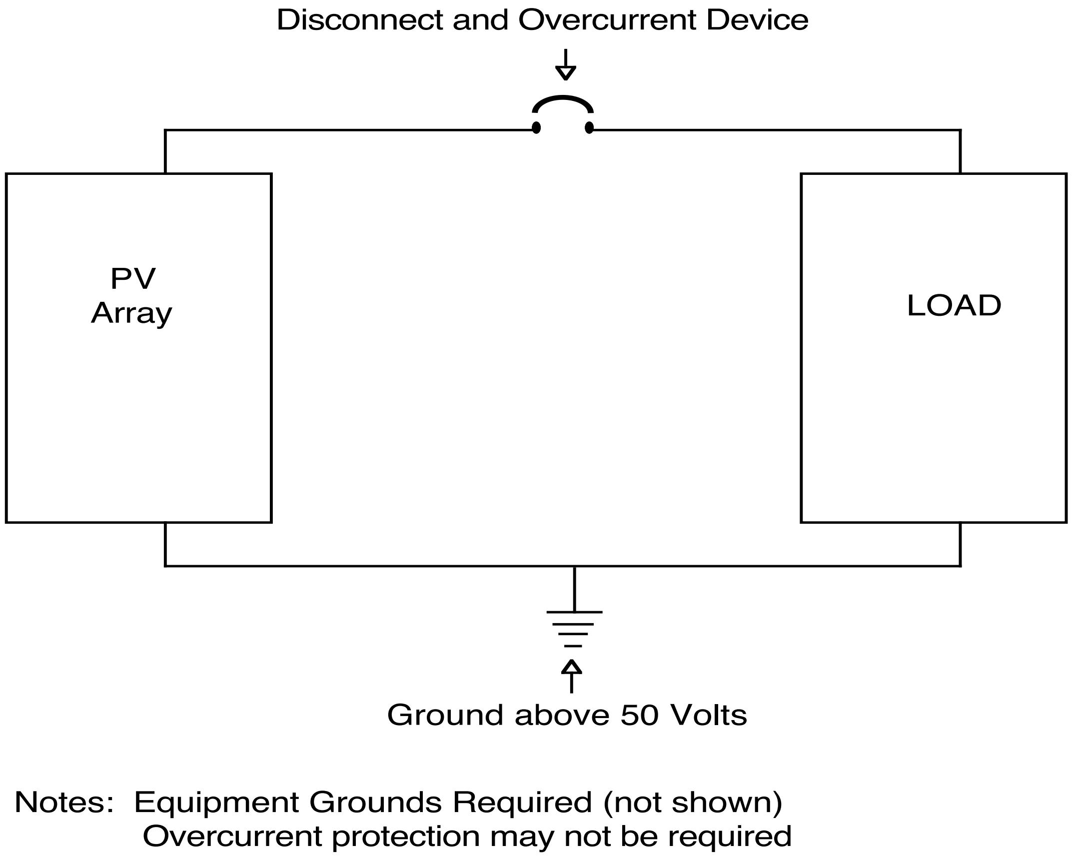


Stand-Alone PV System with Backup Generator and Utility Options


Disconnect and Overcurrent Device
PV
Array
LOAD
Ground above 50 Volts
Notes: Equipment Grounds Required (not shown)
Overcurrent protection may not be required
Direct Connected PV System

Photovoltaic Power System Ratings
NEC Sections 690.53,690.55

Photovoltaic Power Source

Rated Operating Current	43.9 A
Rated Operating Voltage	34.6 V
Maximum System Voltage	55 V (Inc. temp factor)
Rated Short-Circuit Current	47.8 A

Battery System

Maximum Voltage	33 V

Polarity of Grounded Conductor: Negative

Grounding

- All exposed metal surfaces that might be energized shall be grounded with *Equipment Grounding Conductors.*
  —On systems of any voltage
- One of the current-carrying conductors (*Grounded Conductor*) must be grounded if system voltage is 50 V or greater.
  – 12-volt nominal—no ground required, 24-volt nominal and up—ground usually required *(Exception: See 690.35 in 2005 NEC)*
- Only a single bonding jumper is allowed in the dc system
  – Ground-fault protection equipment and U-I inverters usually contain the bonding jumper
- Only a single bonding jumper is allowed in the ac system
- Conductor to the Ground Rod is the *Grounding Electrode Conductor*
- There are exceptions

Grounding-Details

- **Equipment-grounding Conductors—690.45**
  - PV Source Circuits – Sized at 1.25 I_{sc} (*2005 NEC*)
  - — Use I_{sc} in Table 250.122 (*2008 NEC*)
  - AC circuits – Sized per *NEC* 250.122

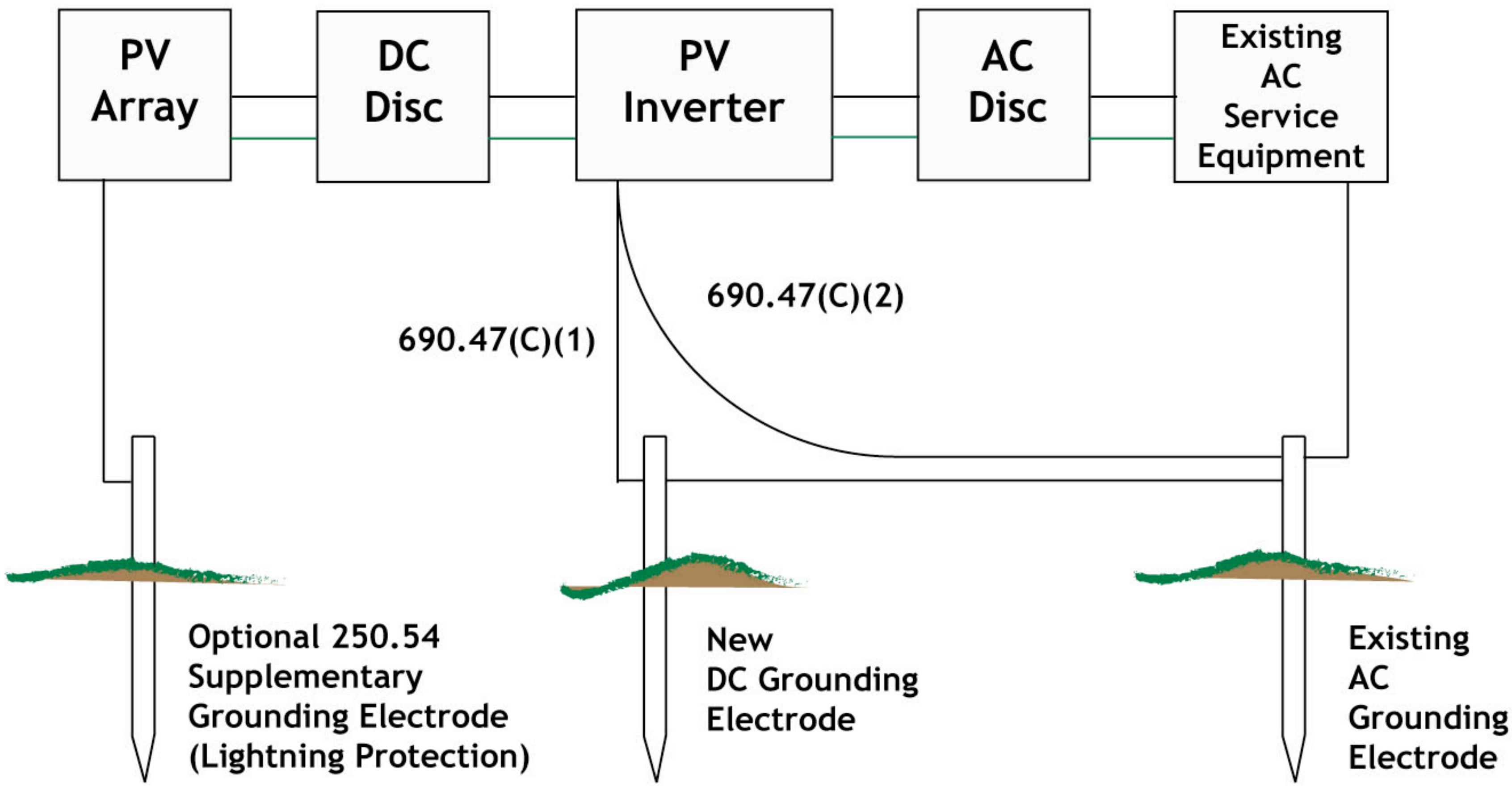
- **Grounding Electrode Conductor (GEC)—690.47**
  - Minimum 6-8 AWG — may have to be larger
  - No splices unless irreversible
  - DC GEC connected to:
    - DC grounding electrode and then bonded to AC grounding electrode

      or
    - The AC grounding electrode

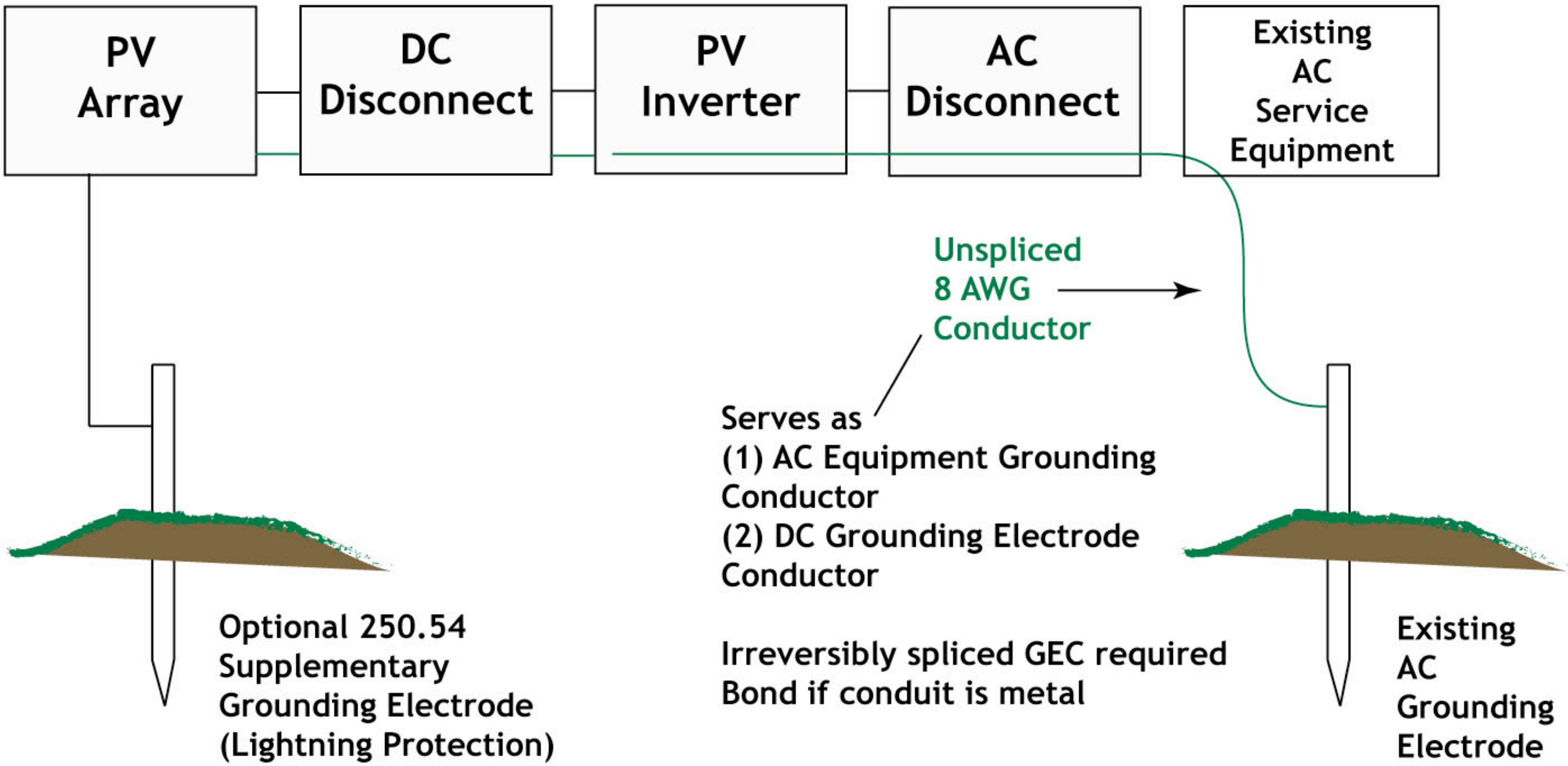
HOT Tips

Never use sheet metal screws to ground boxes
Always bond metal raceways properly over 250 volts

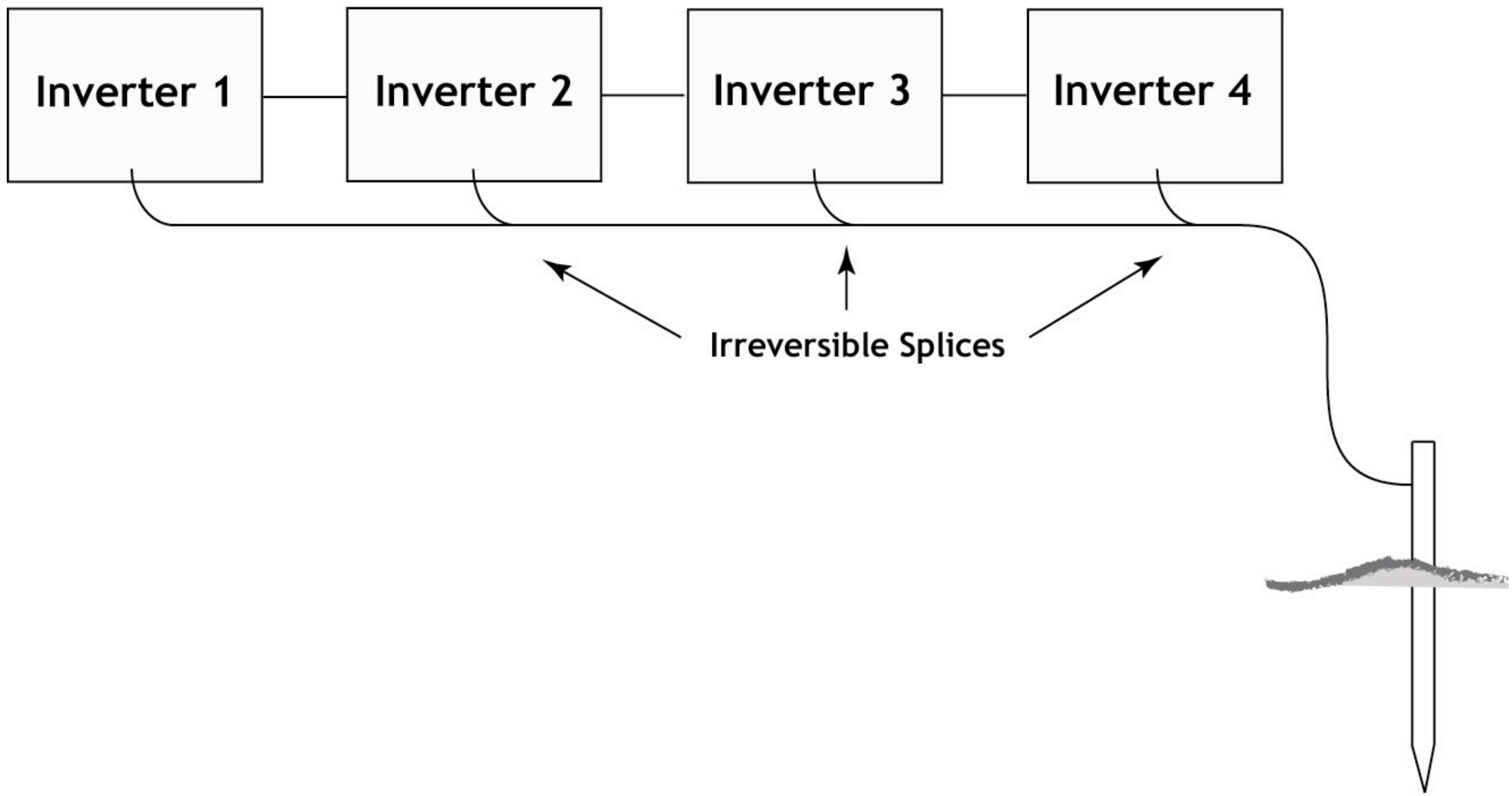
PV Inverter Grounding Methods
2005 *NEC* Section 690.47(C)



PV Inverter Grounding Methods
Alternative



Grounding Multiple Small Inverters



Utility Interconnections

- *NEC* **Requirements**

- **Utility Requirements**
  - Safety (inverter only or full protective relaying)
  - Metering (one to three)
  - Outside Disconnect
  - Contract (net metering/buy back?)

- **Insurance Requirements**

Utility Interconnections

NEC Requirements

- **De-energize on Loss of Power [690.61]**
- **Neutral Conductor Ampacity [690.62]**
  Minimum: Equipment grounding conductor
- **Unbalanced Interconnections [690.63]**
- ***Point of Connection [690.64]***

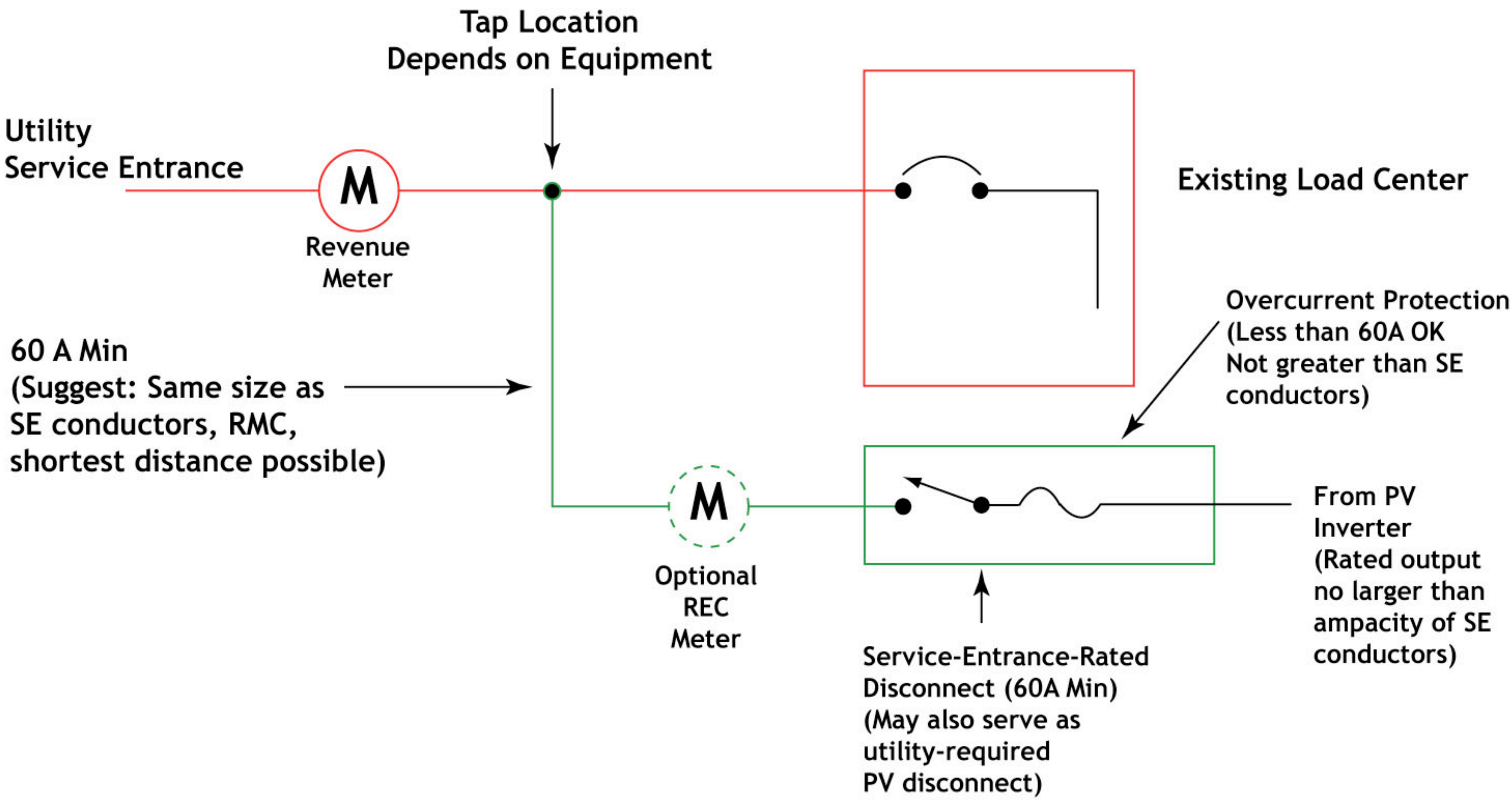
Utility Interconnections

Point of Connection (690.64/705.12(A))

690.64(A)

- **Supply Side of Service Disconnect (230.82(6))**
  - NFPA considers this a second service entrance *(See Appendix M, PV/NEC Manual)*

Supply Side Point of Connection
Service Entrance Tap
NEC 690.64(A)



SupplysideConnection

Supply Side Taps

Combination Meter/Main or Meter/Panel

- Don't tap internally—violates the listing
- Replace with separate meter and main disconnect or panel
- Add new meter base on utility side of existing meter/main
  - Tap between meters, move meter to new base, jumper old base

Zero Sequence CT/PT

- Add new service disconnect, tap on load side or CT/PT
- Install special meter CT/PT disconnect, move CT/PT to supply side

Utility Interconnections
Point of Connection

690.64(B)/705.12(D)

- **Load Side of Service Disconnect**
  - Dedicated Circuit
  - Sufficient Ampacity (Load Center Rating)
  - Line Side of GFCI/GFP
  - Sufficient Marking
  - Backfed Breakers—identified *(690.64(B)(5)-2005 NEC)*

Utility Interconnections
690.64(B)(2)

"The sum of the ampere *ratings* of overcurrent devices in circuits *supplying* power to a busbar or conductor shall not exceed the rating of the busbar or conductor. Exception: 120% for dwelling units."

Utility Interconnections
690.64(B)(2)

Commercial Installation:

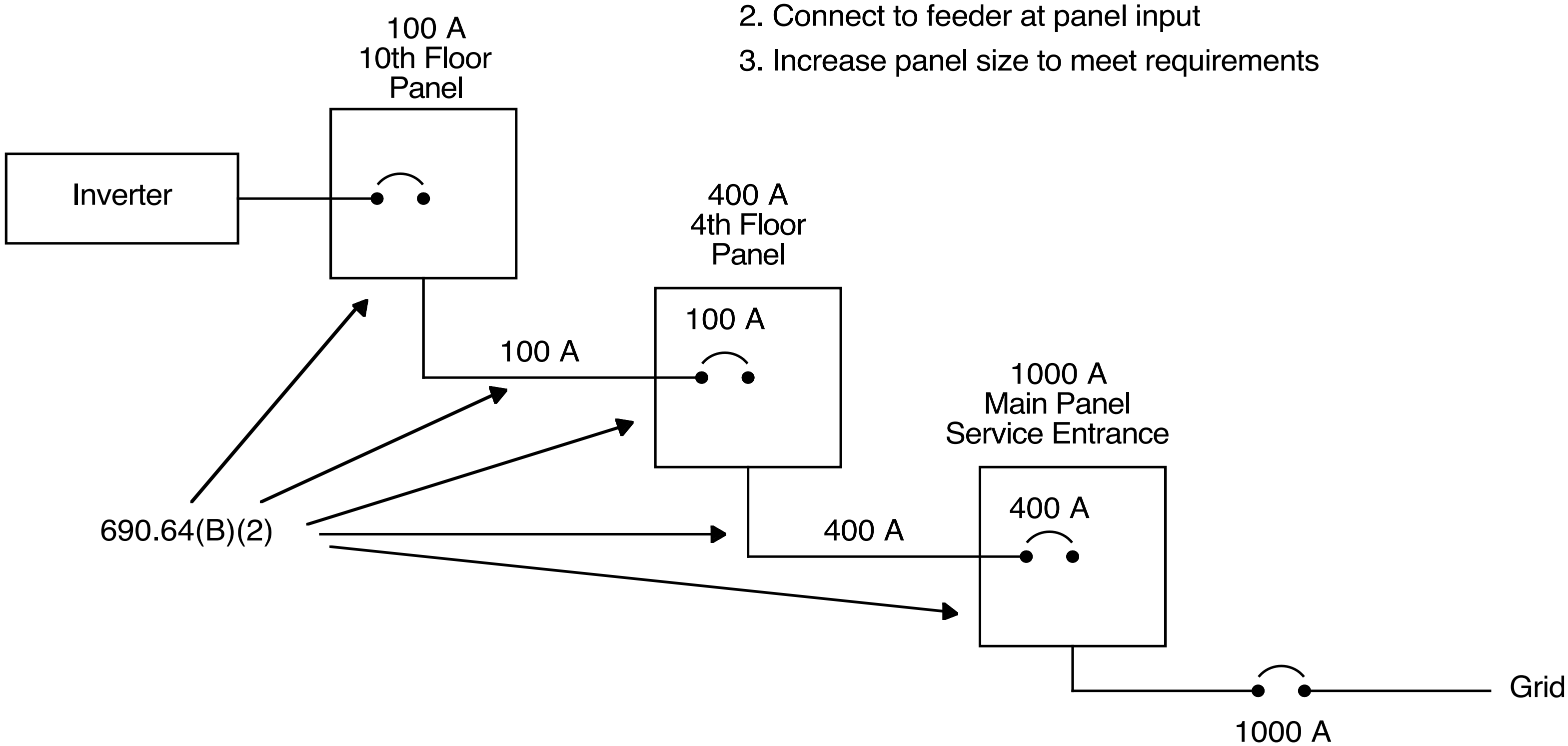
Main Breaker + PV Breaker < = Rating of Load Center, etc.

For PV on Non-Dwellings:

- Increase load center and retain same main breaker
- Carefully assess all circuits back to service entrance
- Use supply (utility) side tap

Commercial Utility Interactive Systems
690.64(B)(2)
PV + Main ≤ Panel

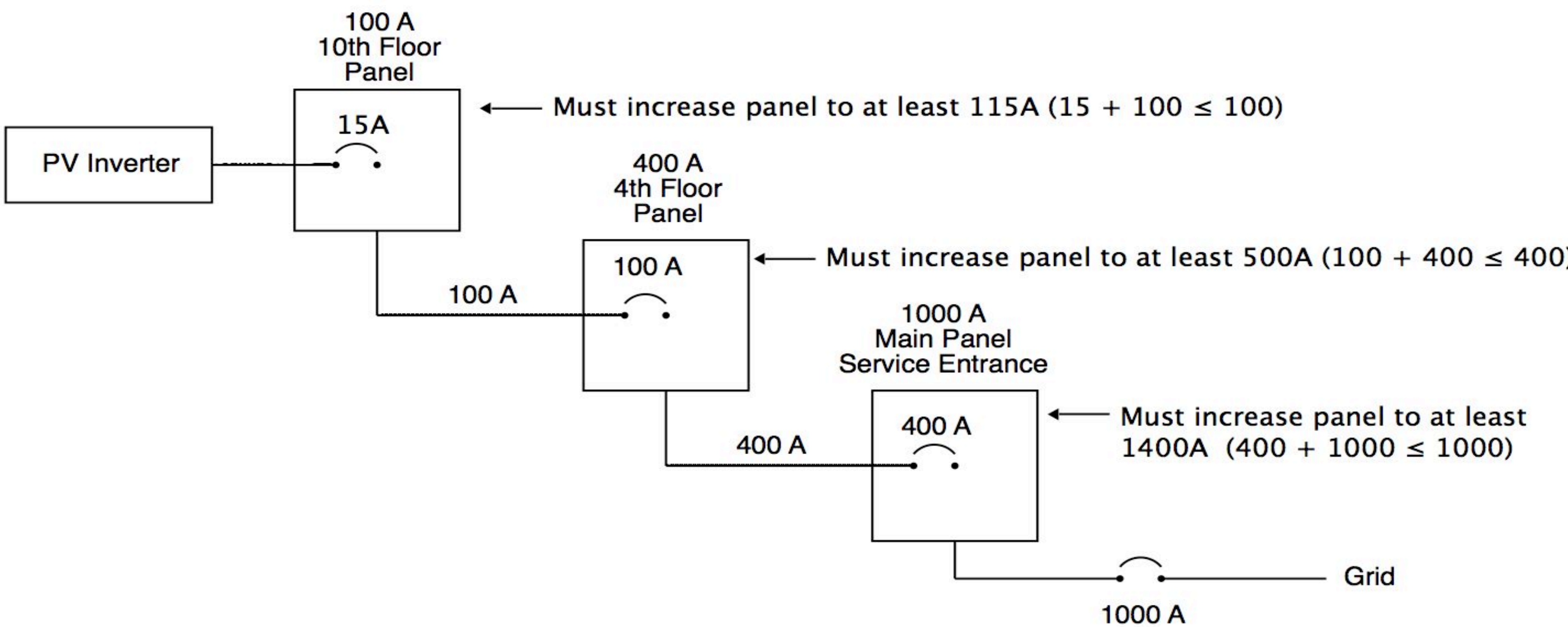
1. If load permits, reduce main breaker by x: Add x PV Breaker
2. Connect to feeder at panel input
3. Increase panel size to meet requirements



After applying 690.64(B)(2) to all of these panels and feeders,
it may be cheaper and easier to just add a second service to the building

2005 *NEC* Requirements
Commercial Utility Interactive Systems
690.64(B)

Backfed PV Breaker + Main Breaker ≤ Panel Rating
Count only backfed breaker directly connected to panel



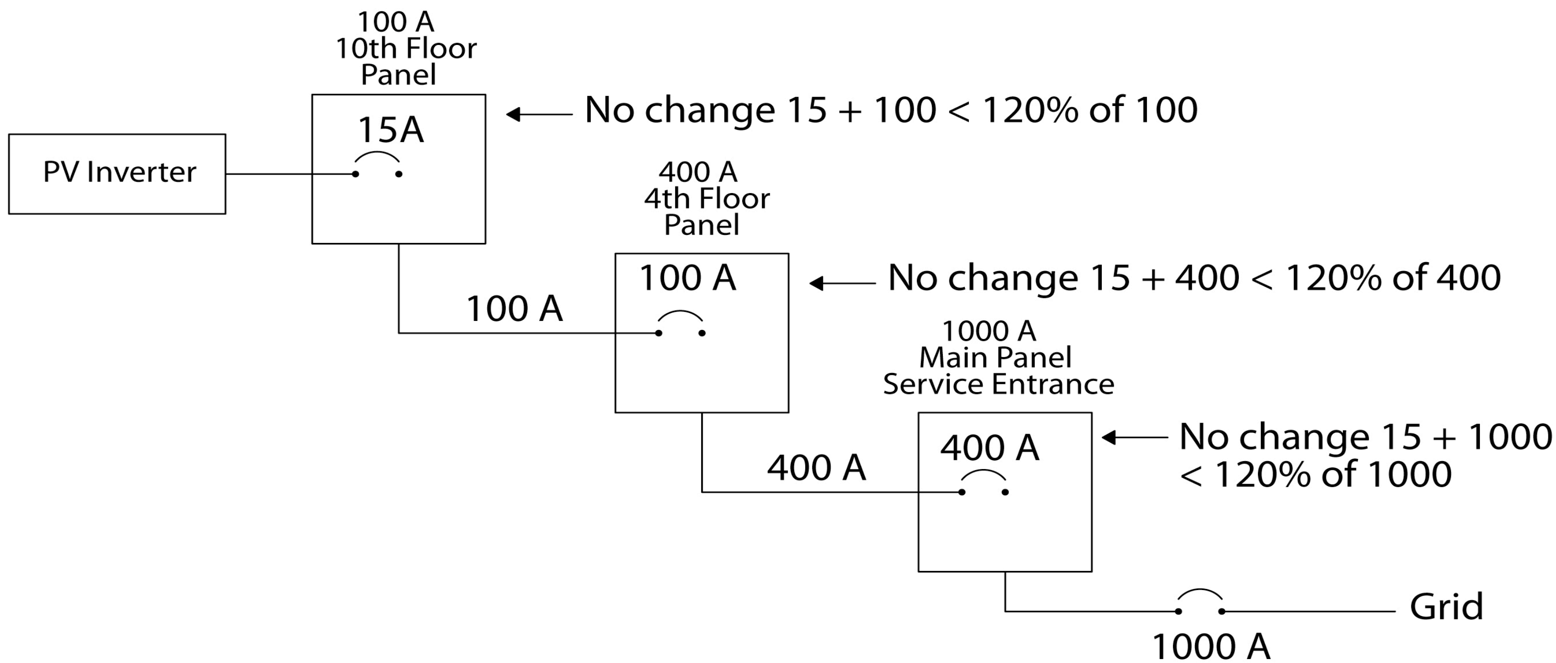
2005 690.64(B)

2008 NEC Requirements
All Utility Interactive Systems
690.64(B)

Backfed PV Breaker + Main Breaker ≤ 120% Panel Rating

Count only the first backfed breaker connected to the inverter

Backfed breaker(s) must be at opposite ends of panel from main breaker



2008 690.64(B)

Load Side Taps--More Details

Meter/Main feeding a main-lug subpanel(s)

- Cannot backfeed breaker in meter/main panel
- Backfed PV breaker must be at “bottom” of subpanel
- Install main breaker in subpanel. Can then backfeed main panel at bottom

Article 240 Tap rules were not developed for multiple sources

- Use 690.64(B)/705.12(D) instead—conductors and bus bars
- Overcurrent device must normally be at the tap point

Center-Fed Panels and multiple-ampacity bus works not covered

- Engineering assessments required

Utility Interconnections 690.64(B)(2)

Dwelling Units Installation:

Main Breaker + PV Breaker < = 120% Rating of Load Center, etc.

For PV on Dwellings:

100 A Load Center/100 A Main Breaker—20 A PV

2 x 2400 W, 120 V Inverters
or 4800 W, 240 V Inverter
Limited by 80% rating on breakers to 3840 W total

200 A Load Center/200 A Main Breaker—40 A PV

2 x 4800 W, 120 V Inverters
or 9600 W, 240 V Inverter
Limited to 7680 W total by breaker ratings

AC Overcurrent Devices

	V_{nom}	I_{nom}	X 1.25	Breaker
SB 2500	240 V	10.4	13 A	15 A
SB 2500	208 V	12.0	15.0	15 A
SB 1800	120	15	18.75	20 A
SB 1100	240	4.6	5.75	10*/15 A

*10 A available on special order

Residential Utility Installations

690-64(B)(2)

The sum of O/C devices supplying power to conductor or busbar must not exceed the rating of that busbar or conductor: Ex: 120% dwelling unit.

<u>Dwelling Unit</u>

100 A panel: PV + main = 120 A →	1 SB 2500 (240 V) 2 SB 1800 (120 V) 1 (15 A) or 2 (10 A) SB 1100
200 A panel: PV + main = 240 A →	2 SB 2500 (240 V) 4 SB 1800 (120 V) 2 (15 A) or 4 (10 A) SB 1100

How to put 3 SB 2500's on a 200 A panel
Use a 100 A Subpanel

- Subpanel Inverter Breakers

  Three SB 2500 → Three 15 A Breakers
- Subpanel Main Breaker

  Main must be 3x10.4x1.25 = 39 → use 40 A main breaker on subpanel. Could also use main-lug panel.
- Subpanel Rating

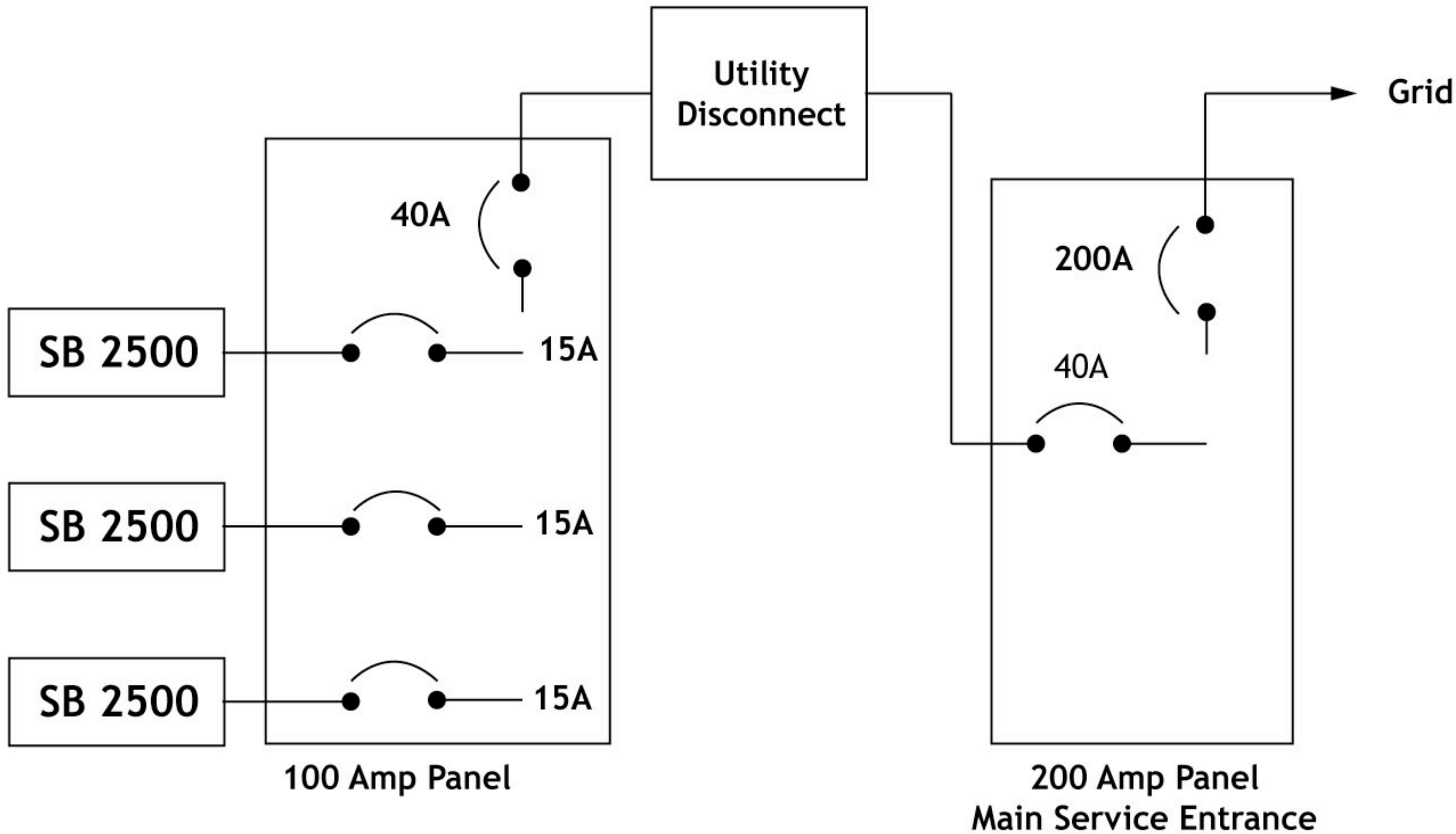
  $45 + 40 \le 1.2 \times$ panel rating

  $85/1.2 \le$ panel rating 71 A → 100 A subpanel
- Main Panel Rating

  Main panel must be 200 A with a 40 A backfed breaker

  $40 + 200 \le 1.2 \times 200 = 240$

Three SB 2500's on a 200 Amp Service



2500 Watt Inverter
AC Voltage Drop/Rise

- **Utility must maintain voltage within 240 V +10%/-12%.**
- **Voltage drop between inverter and meter is seen as voltage rise.**
- **Keep to 0.5% (1.2 V) - 1.0% (2.4 V) or less.**

2500 w @ 240 v = 10.42 A

240 X .005 = 1.2 V

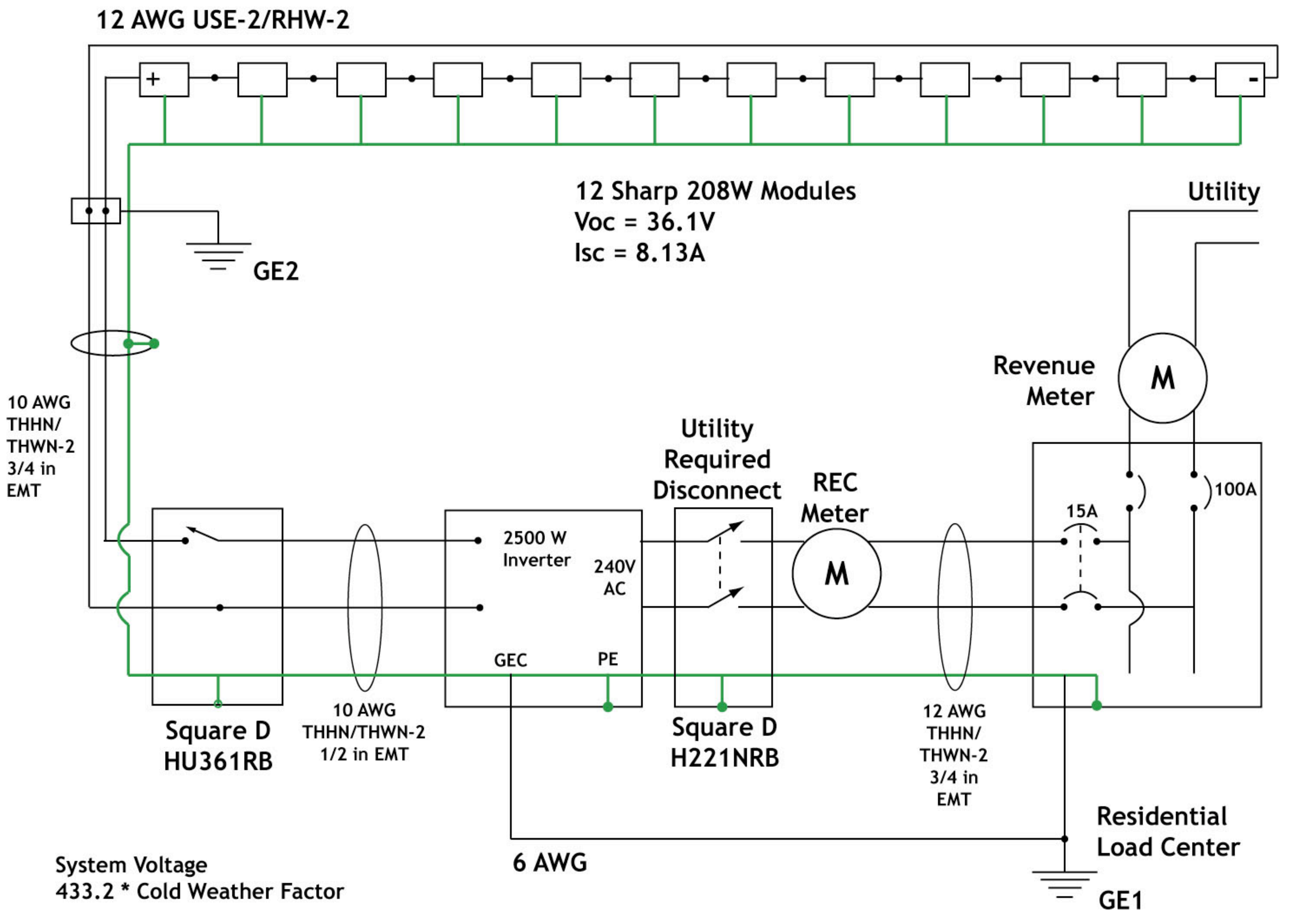
240 X .01 = 2.4 V

R = E/I = 1.2/10.4 = .1154 ohms

2.4/10.4 = .2308 ohms

AWG	Ohms/ 1000 ft	0.5 % VD	1.0% VD
14	3.14	37 ft	74 ft
12	1.98	58 ft	117 ft
10	1.24	93 ft	186 ft

Total of Both Conductors


12 AWG USE-2/RHW-2
+
-
12 Sharp 208W Modules
Voc = 36.1V
Isc = 8.13A
Utility
GE2
Revenue Meter
M
10 AWG THHN/ THWN-2 3/4 in EMT
Utility Required Disconnect
REC Meter
100A
15A
2500 W Inverter
240V AC
M
GEC
PE
Square D HU361RB
10 AWG THHN/THWN-2 1/2 in EMT
Square D H221NRB
12 AWG THHN/ THWN-2 3/4 in EMT
Residential Load Center
6 AWG
GE1
System Voltage
433.2 * Cold Weather Factor

3-wire res PV

Battery Circuits
Observed Problems

- **No overcurrent protection**
- **Improper fuses**
  - AC supplemental
  - Automotive
  - Not listed
  - Sizes
- **Circuit breakers protecting circuit breakers**
  - Not current limiting/limited AIC/AIR
- **No short-circuit protection**
- **Improper cable sizes**

Battery Circuits
Complicating Factors

- High short-circuit currents
- No listed DC current-limiting circuit breakers
- Listed DC fuses & breakers with high AIC
- Fuses must be serviced “Cold” (no voltage)
- Rated inverter input currents not available

PV & *NEC*
Batteries - Cable Selection

- **Battery cables may be 4/0 AWG & higher**
- **Cables must be run in conduit**
- **PV industry has limited experience/equipment**
- **"Battery cables" (Automotive/Marine) are not recognized by *NEC***
- **Welding cables are listed by UL only for welders**
- **Flexible USE, RHH, RHW, and THW cables are available & acceptable *but must be used with special terminals*.**

PV & *NEC*
Batteries - High Short-Circuit Currents

- Deep-Cycle storage batteries can deliver high short-circuit currents
- One 220-A-h, 6 V golf cart battery can deliver 6000-8000 A into a short circuit
- Some DC-rated overcurrent devices have limited short-circuit interrupting capabilities
- Current-limiting fuses (types RK-5, RK-1, T) are required on all circuits leaving battery—High AIC circuit breakers throughout are a substitute
- *Current limiting fuses cannot protect dc breakers*
- Disconnect switch must be between battery & fuse

Cables, Disconnects, Overcurrent Protection

Trace SW4024

Battery-to-Inverter Cables (from Factory Specs)

- Rated AC Output Power: 4000 W (Listed)
- Lowest Battery Voltage: 22 V
- Efficiency: 85% at rated power
- Calculated DC Input Current (with external charger)
  $4000 \div 22 \div .85 = 214$ A
- *NEC* 125% Factor: $214 \times 1.25 = 267$ A

Cables, Disconnects, Overcurrent Protection

Trace SW4024 (continued)
Battery-to-Inverter Cables

- **Assume: 30°C Temperature and 75°C Terminals**
- **Conduit Required (*NEC* Table 310.16)**
- **300 Kcmil 75°C cable carries 285 A at 30°C**
- **Parallel 2/0 AWG carries 175 x 2 = 350 A at 30°C**
  - 4 conductors in conduit: 80% derating
  - 350 x .8 = 282 A
- ***Manual suggests single 4/0 AWG cable @ 230 A***

Cables, Disconnects, Overcurrent Protection

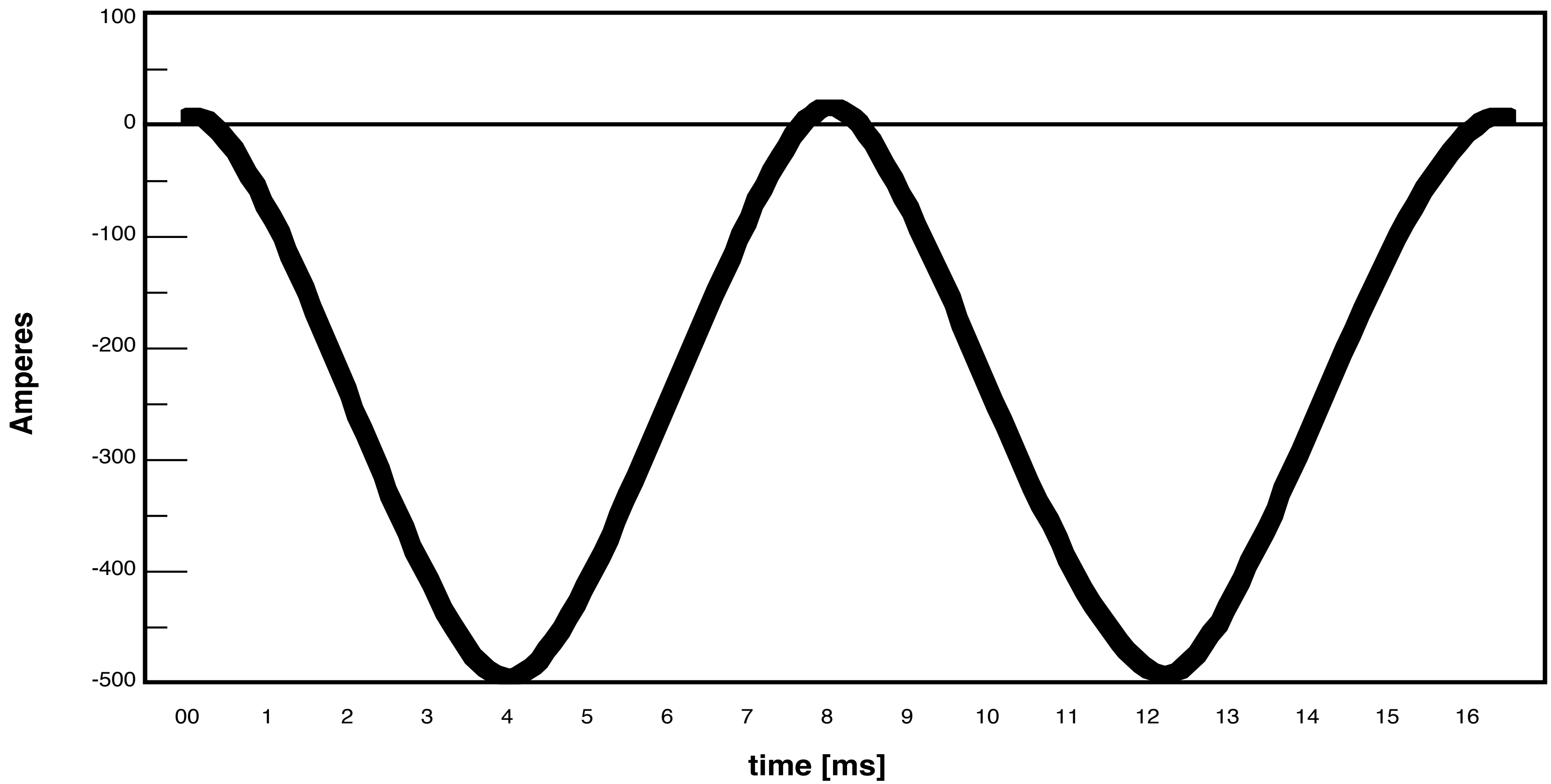
Trace SW4024 (continued)

DC Overcurrent Devices

- **300 A Fuse**
  - Fused Disconnect
  - Pull-Out Fuse Holder (must be load-break rated—or marked)
  - Use High-AIR fuses throughout the system
- **250-300 A Circuit Breaker** (rated for 100% operation in the enclosure)
  - Cannot protect other overcurrent devices
- **Mounted Near Battery**

Sunwize SW-1200 Hybrid PV System

Inverter Current Waveform (DC Side)



Load Power = 4000 Watts
Battery Voltage = 22.0 Volts

Current Average = -254.2 Amperes
Current RMS = 311.3 Amperes

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Trace SW4024 (continued)
Large Systems

Test Data: At 22 V and 4000 W Resistive Load

Measured Inverter DC Input Current:

Average	254 A
RMS	311 A

RMS currents should be used for sizing cables and overcurrent devices.

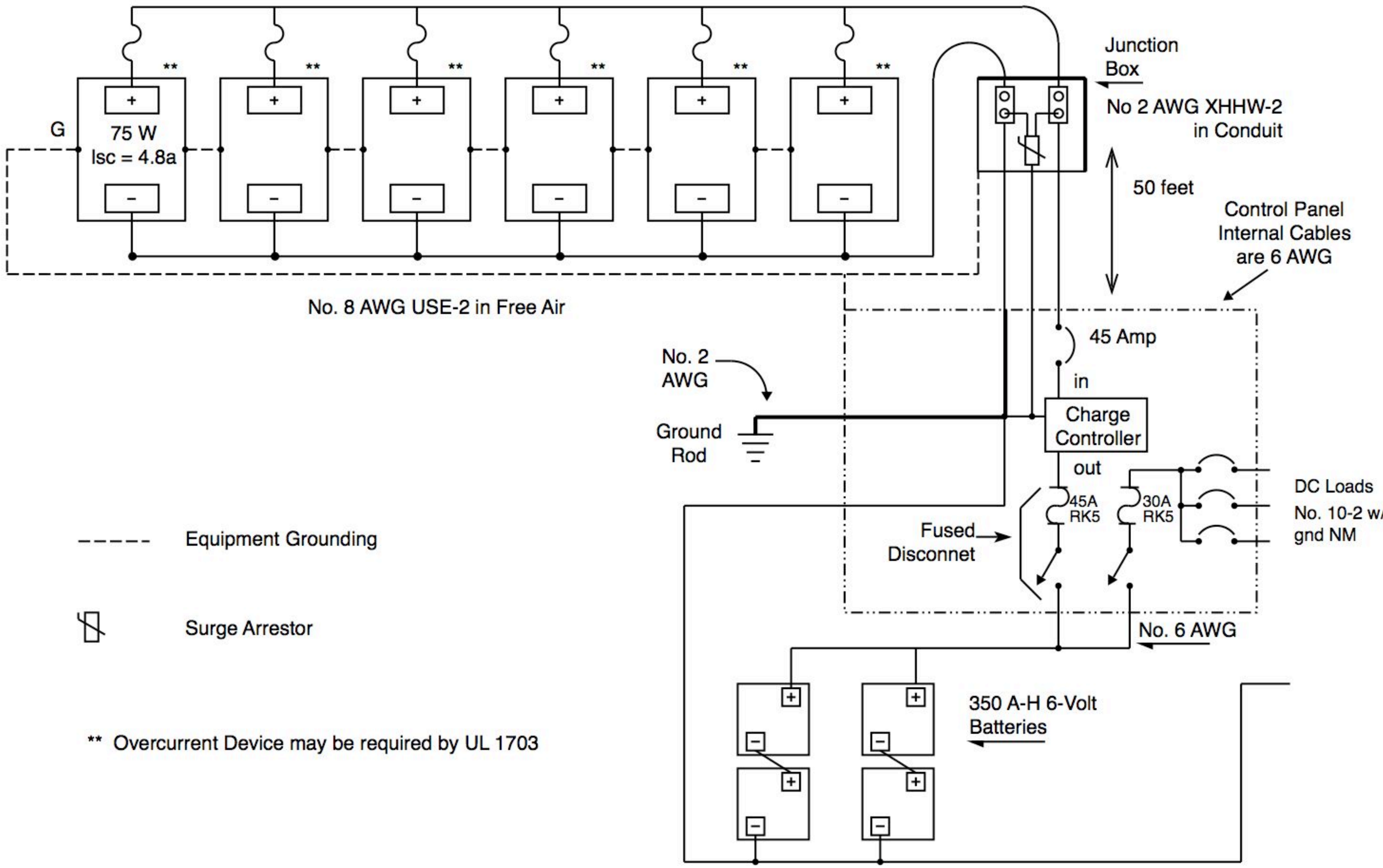
Nuisance tripping of circuit breakers rated at 250 A is possible.

If 350-amp fuses are used, cables must be sized appropriately.

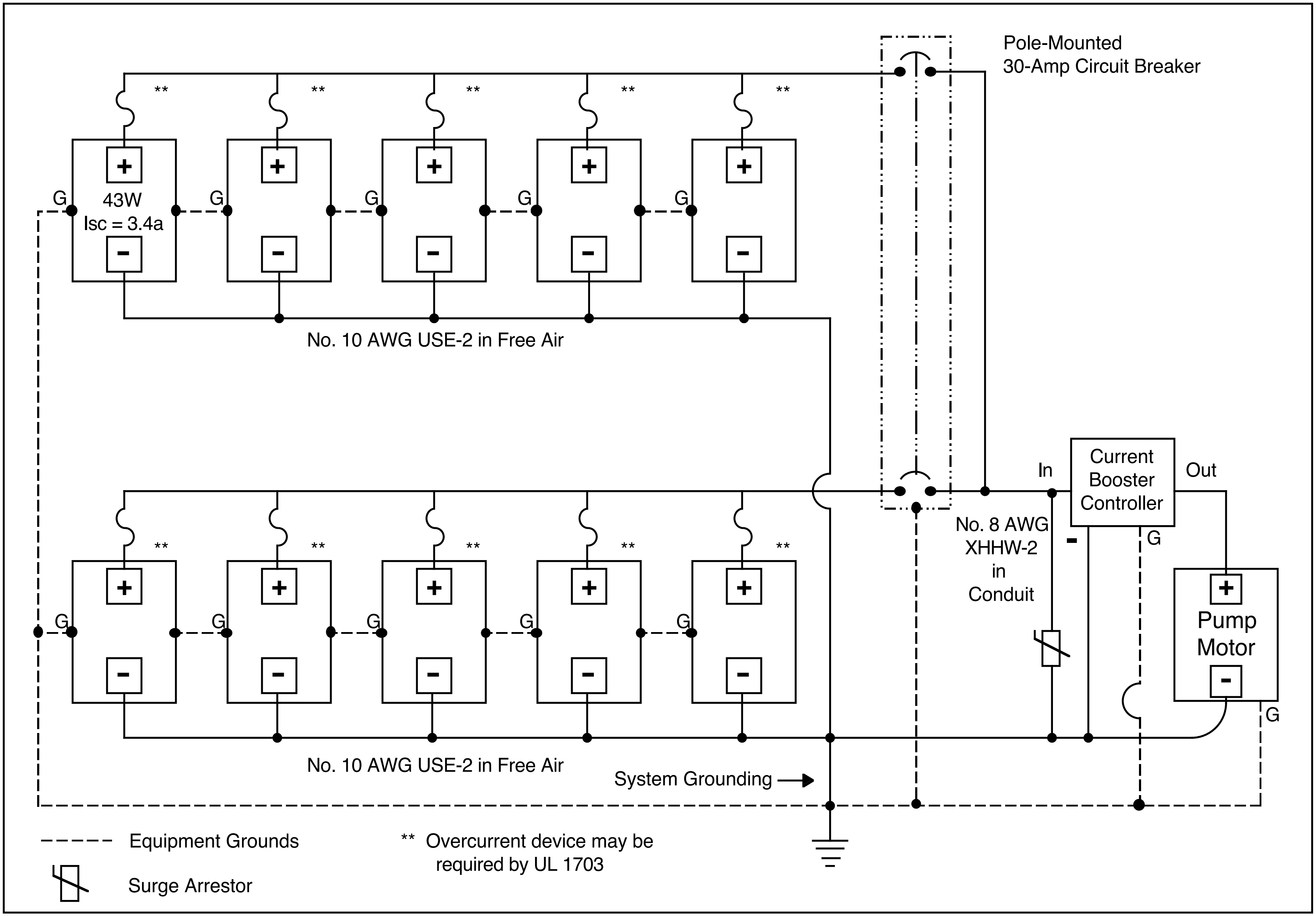
Cables, Disconnects, Overcurrent Protection

Trace SW4024 (continued)
AC Output Circuits

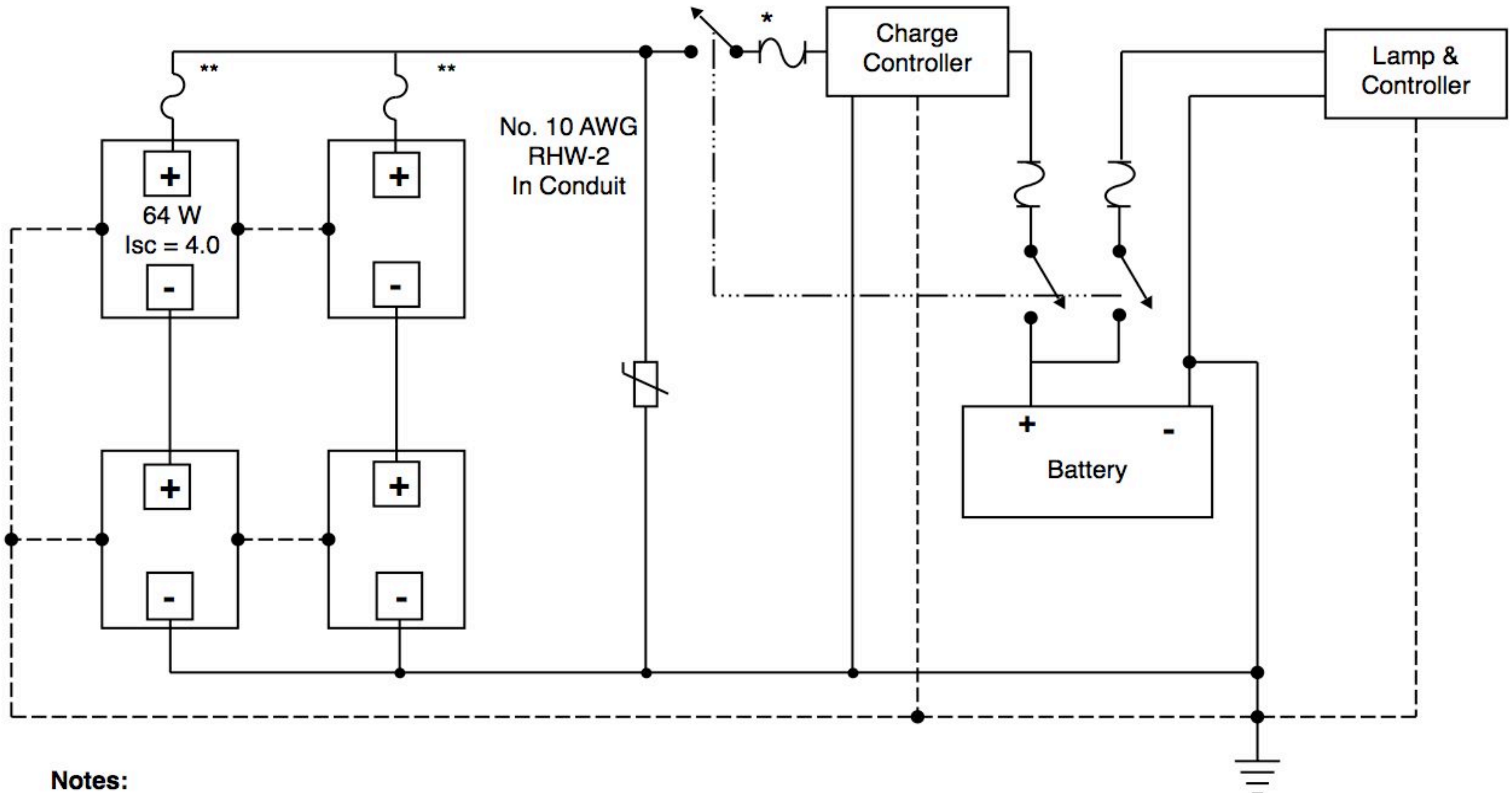
- **Rated feed through from AC-1 or AC-2: 60 A**
- **Maximum steady-state output current: 60 A**
- **Required cable ampacity 60 x 1.25 = 75 A**
- **4 AWG cable at 30°C and 75°C insulation = 85 A**
- **SW4024 can take 6 AWG maximum: 65 A**
- **Unusual to have these outputs for hours at a time**
- **Use 6 AWG, 90°C cable (65 A at 75°C)**
  - Protect with 70 A breaker rated for 100% duty



INSP-85
INSP-85



Pole-Mounted
30-Amp Circuit Breaker
G
43W
Isc = 3.4a
**
No. 10 AWG USE-2 in Free Air
In
Current
Booster
Controller
Out
No. 8 AWG
XHHW-2
in
Conduit
Pump
Motor
No. 10 AWG USE-2 in Free Air
System Grounding
Equipment Grounds
** Overcurrent device may be
required by UL 1703
Surge Arrestor



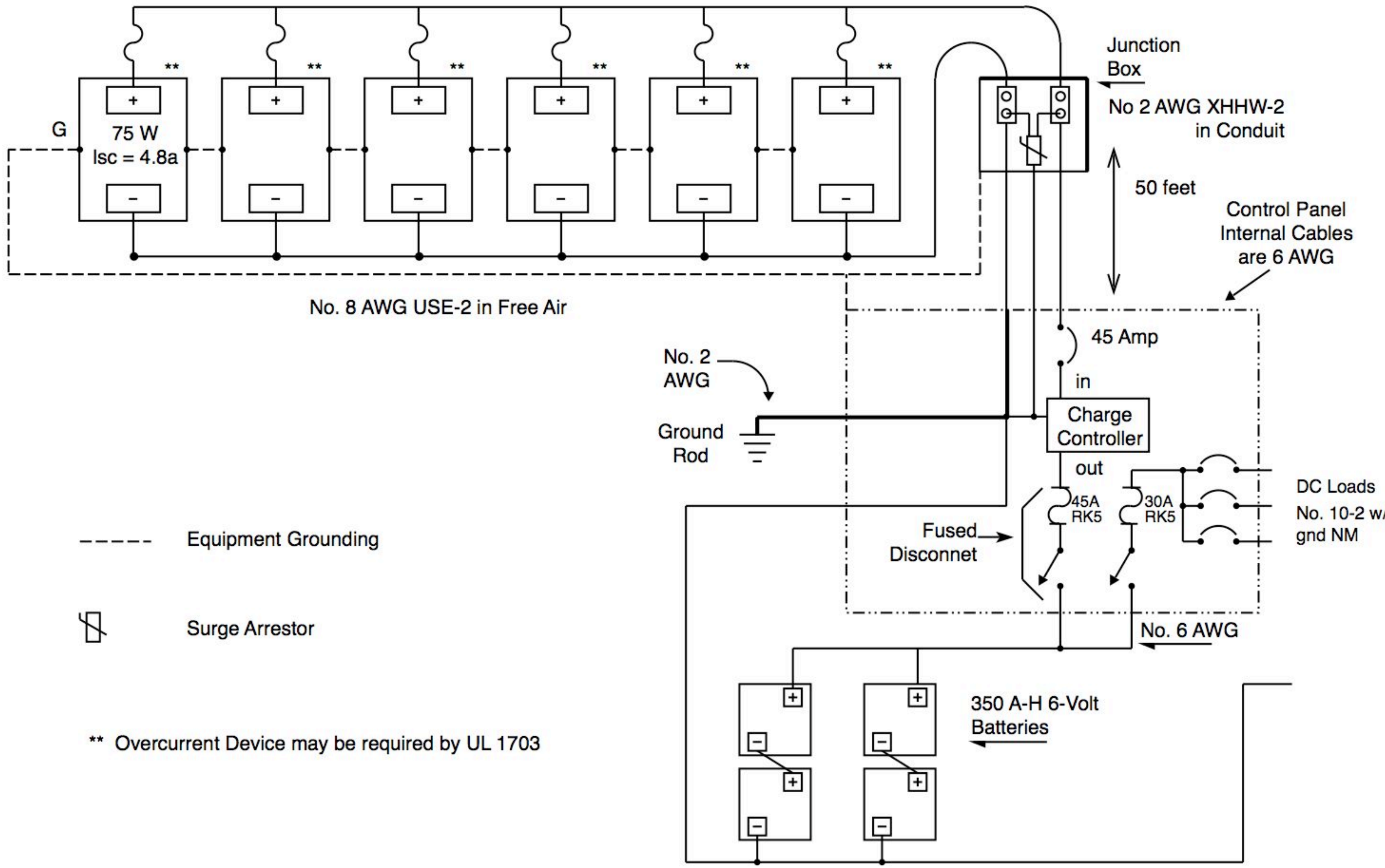
Notes:

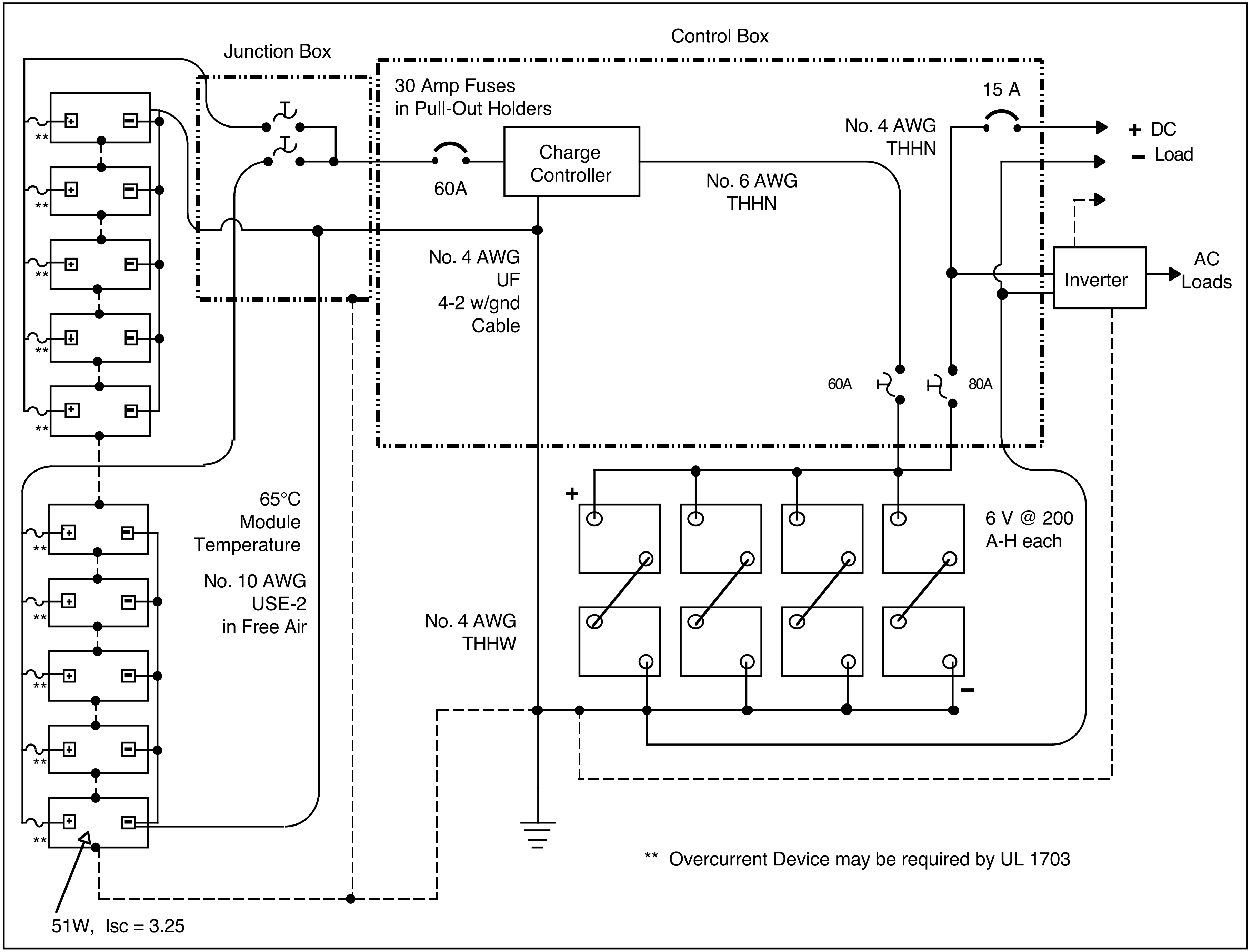
** Overcurrent device may be required by UL 1703

* Optional Fuse

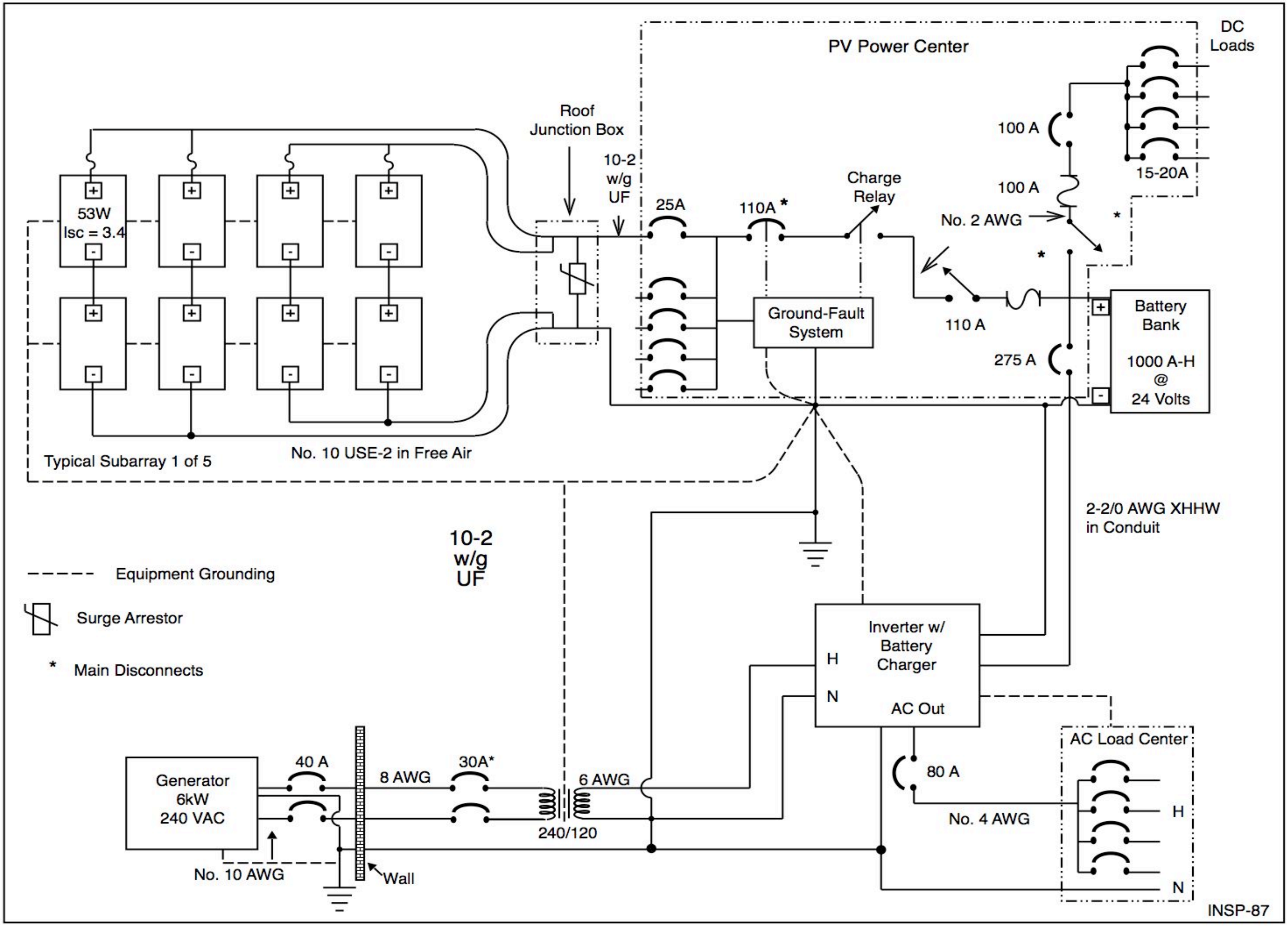
– – – – Equipment Grounds

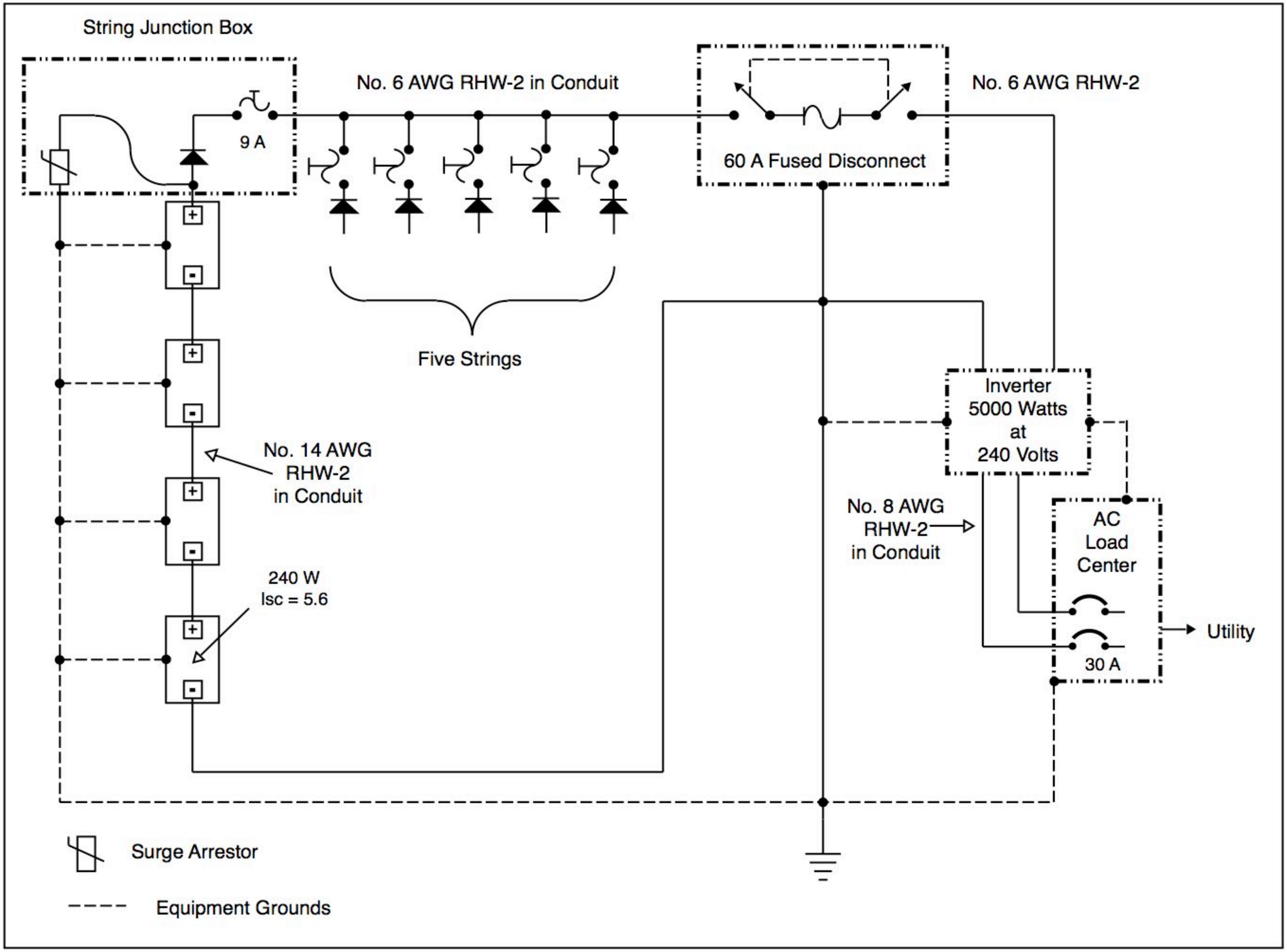
Surge Arrestor

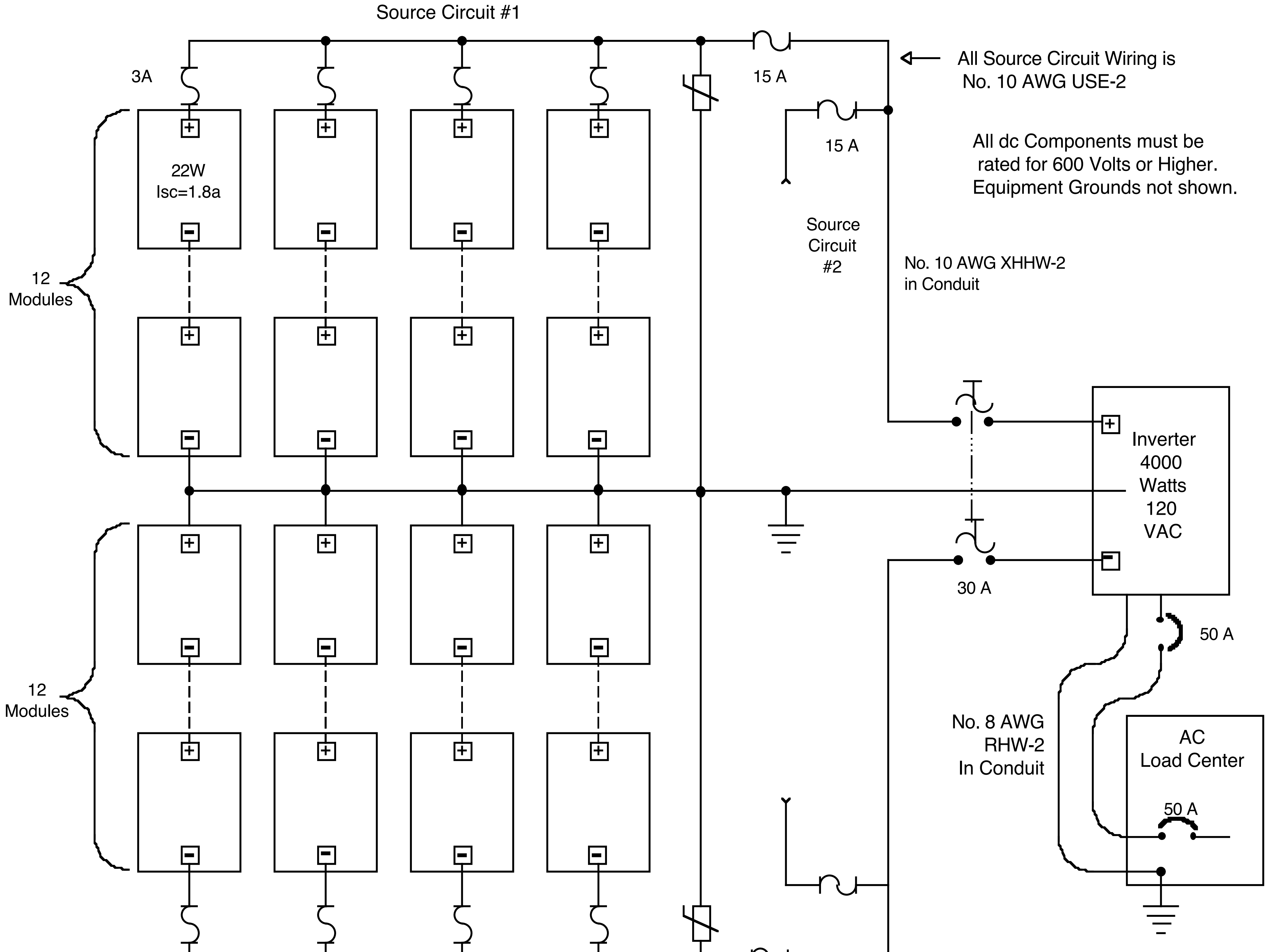

Junction
Box
No 2 AWG XHHW-2
in Conduit
G
75 W
Isc = 4.8a
**
+
−
50 feet
Control Panel
Internal Cables
are 6 AWG
No. 8 AWG USE-2 in Free Air
No. 2
AWG
45 Amp
in
Ground
Rod
Charge
Controller
out
45A
RK5
30A
RK5
DC Loads
No. 10-2 w/
gnd NM
Fused
Disconnet
Equipment Grounding
Surge Arrestor
No. 6 AWG
350 A-H 6-Volt
Batteries
** Overcurrent Device may be required by UL 1703



2/23/07 INSP-262

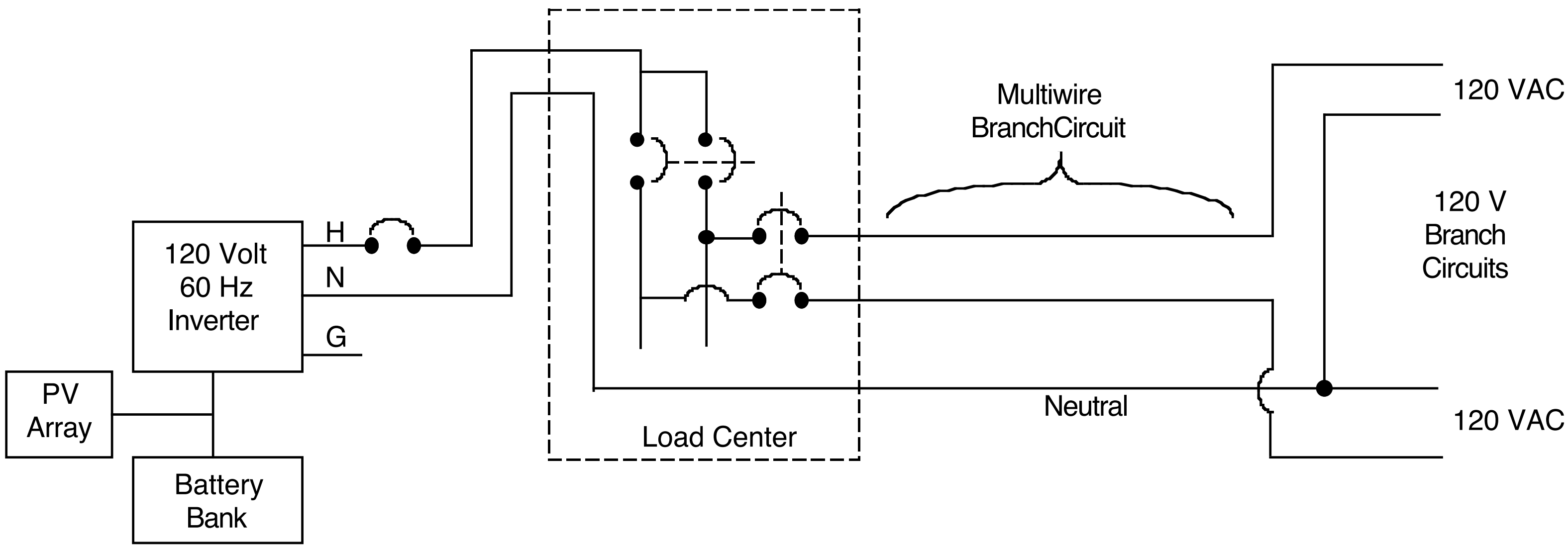

PV Power Center
DC Loads
Roof Junction Box
10-2 w/g UF
25A
110A *
Charge Relay
100 A
100 A
15-20A
No. 2 AWG
*
*
53W
Isc = 3.4
Ground-Fault System
110 A
275 A
Battery Bank
1000 A-H @ 24 Volts
Typical Subarray 1 of 5
No. 10 USE-2 in Free Air
2-2/0 AWG XHHW in Conduit
10-2 w/g UF
Equipment Grounding
Surge Arrestor
* Main Disconnects
Inverter w/ Battery Charger
H
N
AC Out
80 A
AC Load Center
H
N
No. 4 AWG
Generator 6kW 240 VAC
40 A
8 AWG
30A*
6 AWG
240/120
No. 10 AWG
Wall
INSP-87


String Junction Box
No. 6 AWG RHW-2 in Conduit
9 A
No. 6 AWG RHW-2
60 A Fused Disconnect
Five Strings
Inverter
5000 Watts
at
240 Volts
No. 14 AWG
RHW-2
in Conduit
No. 8 AWG
RHW-2
in Conduit
AC
Load
Center
240 W
Isc = 5.6
Utility
30 A
Surge Arrestor
Equipment Grounds



2/23/07 INSP-265

Safety Alert
Multiwire Branch Circuits and PV Systems



- **Inverters—250 W - 8 kW @ 120 V**
- **Load Centers—120/240 V @ 100 - 200 A**
- **Multiwire Branch Circuits—common**
- **Neutral Overload Possible**

Southwest Technology Development Institute

College of Engineering
Institute for Energy & the Environment

Multiwire Branch Circuits
Section 690.10(C)

(c) Single 120-Volt Supply. The inverter output of a stand-alone solar photovoltaic system shall be permitted to supply 120 V to single-phase, 3-wire 120/240 V service equipment or distribution panels where there are no 240 V outlets and where there are no multiwire branch circuits. In all installations, the rating of the overcurrent device connected to the output of the inverter shall be less than the rating of the neutral bus in the service equipment. This equipment shall be marked with the following words:

WARNING—SINGLE 120 VOLT SUPPLY
DO NOT CONNECT MULTIWIRE BRANCH CIRCUITS!

Multiwire Branch Circuits
How to Correct the Problem

- Rewire multiwire circuit as separate home runs.
- Connect both ungrounded conductors to a single circuit breaker—wire nut may be required.
- Limit output breaker on inverter to ampacity of multiwire branch circuit neutral. Add warning.
- Add second inverter to get 120/240 V system.
- Use transformer to get 120/240 V output from single inverter.

2008 *NEC*

- 120% on 690.64(B) for non-dwelling installations
- Revisions to grounding
- Clarification of 250.166, size of DC GEC
- Ground-fault protection on all systems
- "PV Wire" for ungrounded systems
- 5°C Table for 690.7 or use manufacturer's data
- No requirements for batteries or generators, except…
- Inverter or generator must serve largest connected load
- DC/PV Metallic cable assemblies NOT allowed inside buildings
- Must use proper terminals on fine-stranded, flexible cables
- Grounding electrode required for PV array grounding

PV & *NEC* Summary

- NEC applies to most PV systems
- DC-rated equipment is required
- Most wiring methods are familiar
- Cable selection & sizing require added consideration
- Battery circuits need attention to high currents

- The Trinity:
  - PV Designer
  - ”Code Familiar” Person
  - The Inspector/Plan Reviewer

- RESULT: Safe, Durable, Reliable and Cost Effective PV SYSTEMS

FOR MORE INFORMATION on
PHOTOVOLTAIC POWER SYSTEMS and the NATIONAL ELECTRICAL CODE

Southwest Technology Development Institute, New Mexico State University
web site: http://www.nmsu.edu/~tdi Go to PV, then Codes and Standards

2005 PV/NEC Suggested Practices Manual:
http://www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/PVnecSugPract.html

Sandia National Laboratories—web site: http://www.sandia.gov/pv/

2008 *NEC* and *NEC Handbook* available from NFPA:
custserv@nfpa.org http:// www.nfpa.org

IAEI Soares Book on Grounding and ***IAEI News*** available from:
International Association of Electrical Inspectors (IAEI). http://www.iaei.org

Home Power Magazine—web site: http://www.homepower.com
Conduit temp data:

UL White Book **http://www.ul.com/regulators/2006WhiteBook.pdf**

Conduit Temperature data:
http://www.copper.org/applications/electrical/building/derating_table.html